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FINAL REPORT

THE DESIGN AND OPERATION OF A PILOT PLANT ON URANIUM BIOSORPTION

by

Dr. Marios Tsezos

Work on this project was conducted under contract file DSS-23440-8-9156/01SQ.
Scientific Authority: Dr. R.G.L. McCready, Head CANMET Biotechnology Section

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1. Uranium Biosorption Results
2. Uranium Elution Results

EXECUTIVE SUMMARY

Inactive microbial biomass of the type Rhizopus arrhizus was immobilized in particulate from using the proprietary technology that has been developed by Dr. Marios Tsezos, at McMaster University in Hamilton, Ontario, Canada. A continuous upflow packed bed reactor was designed, constructed and charged with the immobilized biomass. the column was 40 inches long, had an inside diameter of 2.5 inches and was charged with about 2 lb of immobilized biomass. The column feed was pH = 4, settled, biological leachate supplied by Denison Mines from their Elliot Lake uranium biological leaching works with an average initial uranium concentration of about 140 mg/L. The column was designed to continuously extract the uranium from the biological leachate and to recover it in the form of a concentrated eluate. The pilot plant was operated for about 14 months. To date, these experiments have been the largest pilot plant using immobilized biomass in a column for the concentration of a chemical compound. Up to 100 fold concentration of the uranium was achieved using sodium bicarbonate as the eluant. Uranium concentrations as high as 14 g/l were reached. The behaviour of several other elements present in the bioleach solutions was also examined. Each element presented specific loading and elution characteristics and the biosorption of uranium from bioleach solutions constituted a complex system. The selectivity of the process for uranium was conclusively demonstrated, as well as the possibility of using the immobilized biomass to separate aluminum yttrium and rare earths from uranium and thorium. A hypothesis on the influence of iron, aluminum, silicon, and thorium on uranium biosorption was advanced. The implemented pretreatment of the pilot plant feed however was such that allowed the gradual accumulation of competing ions in the active biomass regions thus gradually reducing the average uranium capacity of the

immobilized biomass packed bed. This project demonstrated conclusively the ability of the immobilized biomass particles to operate over long periods of continuous industrial type use. The kinetic properties of the immobilized biomass particles remained robust over that period of time. Appropriate feed solution pretreatment should provide the answer to the uptake capacity problems observed. This technology, characterised by high selectivity, can be used not only to remove and/or recover uranium from dilute complex wastewaters or industrial solutions but also as a specific separation/recovery technology for metals, like uranium, thorium, yttrium and aluminum and for the treatment of radioactive waste waters.

RÉSUMÉ

La biomasse inactive de l'espèce microbienne Rhizopus arrhizus a été immobilisée sous forme de particules grâce à une technologie développée à l'Université McMaster à Hamilton, Ontario, Canada, par M. Marios Tsezos, qui en est propriétaire. Un réacteur à lit compact fonctionnant par flux ascendant a été conçu, construit à CANMET et chargé de la biomasse immobilisée. La colonne faisait 40 pouces de long, possèdait un diamètre interne de 2.5 pouces et contenait environ 2 lb de biomasse immobilisée. La colonne a été alimentée d'un lixiviat biologique de pH=4, de concentration moyenne d'uranium de 140mg/L, provenant des installations où s'effectue la biolixiviation de l'uranium, dans les mines Denison à Elliot Lake. La colonne a été conçue pour extraire en continu l'uranium du lixiviat biologique, et le récupérer sous forme d'éluat concentré. Le laboratoire pilote a fonctionné pendant environ 14 mois. Jusqu'à date, il représente le plus gros laboratoire pilote jamais utilisé pour la concentration d'un composé chimique à l'aide d'une colonne chargée de biomasse immobilisée. L'utilisation du bicarbonate de sodium comme éluant a permis d'obtenir une solution d'uranium jusqu'à 100 fois plus concentrée. Des concentrations d'uranium qui s'élevent à 14g/L ont été obtenues. Le comportement de d'autres éléments présents dans les biolixiviats a aussi été étudié. Chaque élément possédait des charactéristiques spécifiques d'adsorption et d'élution, la biosorption de l'uranium à partir de biolixiviats constitue un system complexe. La sélectivité du procédé pour l'uranium a été démontrée, ainsi que la possibilité d'utiliser la biomasse immobilisée pour séparer l'aluminium, l'yttrium et les terres rares de l'uranium et du thorium. Une hypothèse qui porte sur l'influence du fer, de l'aluminium, du silicium et du thorium sur la biosorption de l'uranium a été formulée. Le type de prétraitement appliqué au biolixiviat avant passage dans la colonne était tel que, graduellement, des ions compétitifs pour l'uranium se sont accumulés dans la biomasse et la capacité moyenne d'absorption du réacteur à lit compact contenant de la biomasse

immobilisée a diminué pour l'uranium. Ce projet a démontré de façon concluante que les particules de biomasse immobilisée peuvent être utilisées en continu pendant de longues périodes de temps semblables à ce qu'on retrouve en industrie. Au cours de ces expériences les propriétés cinétiques des particules de biomasse immobilisée sont demeurées constantes. Un meilleur prétraitement du biolixiviat avant passage dans la colonne devrait permettre de résoudre les problèmes observés pour la capacité d'absorption. Cette technologie, qui se charactérise par sa grande sélectivité, peut servir non seulement à éliminer et/ou à récupérer l'uranium à partir d'eaux usées diluées complexes ou de solutions industrielles, mais aussi comme une technologie de séparation/récupération spécifique pour des métaux comme l'uranium, le thorium, l'yttrium et l'aluminium et pour le traitement d'eaux usées radioactives.

THE DESIGN AND OPERATION OF A CONTINUOUS PILOT PLANT ON URANIUM BIOADSORPTION

1. INTRODUCTION

1.1 Project Scope and Objectives

Denison Mines, in co-operation with the Department of Energy, Mines and Resources, is conducting in situ bioleaching of uranium ore underground. The volumes of leachate encountered in bioleaching are, understandably, large and low in uranium concentration. The cost, of pumping millions of gallons per day of such leachate, is high and it is desired to determine the best process design to recover uranium from these dilute solutions.

In the past ten years, a proprietary process for immobilization of microbial biomass has been developed at McMaster University by Dr. M. Tsezos. In 1987, a continuous mini pilot plant using 32 g of immobilized Rhizopus arrhizus biomass in an upflow column was operated. This pilot plant yielded uranium peak concentrations corresponding to a 30-fold concentration of the initial uranium present in the Denison Mines bioleach solutions that contained 300 mg U/l. A total of 16 loading-elution cycles were completed with no apparent loss of efficiency after the second cycle. Following these encouraging results, additional immobilized biomass was produced at McMaster University by Dr. M. Tsezos and it was decided to operate a larger pilot plant to test further this new technology. The present project focusses on the operation of this larger pilot plant. The main objectives of the present contract are as follows:

1. To design, set up and debug a uranium biosorption pilot plant to be located on CANMET's Biotechnology section premises that are suitable

for such larger scale work. The pilot plant would operate during the uranium loading part of the cycle (beginning of the cycle) with pH = 4 settled bioleach solution, in a packed bed upflow mode at a fixed flow rate charged with the same type of immobilised biomass that has been used by Dr. M. Tsezos in the mini plot plant. The pilot plant will have provisions to wash the immobilised biomass at the end of the loading cycle with a fixed volume of water. Then the reactor would be switched to the uranium elution mode by passing through a fixed volume of sodium bicarbonate eluant at a Solid to Liquid ratio of about 20:1 mg/mL. After elution the biomass bed will be washed again with water and revert again to the beginning of a new uranium recovery cycle.

2. The pilot plant operation would be monitored by Dr. M. Tsezos over the entire duration of the project.

3. The results from the pilot plant operation would be critically reviewed and compared to the results from the mini pilot plant previously operated by Dr. M. Tsezos. Suggestions for changes in the operational conditions of the pilot plant would be made if deemed necessary,.

A disruption in the supply of mine water from Denison Mines led to the development of a contaminating biological growth on the idle immobilized biomass bed. Proper treatment of the bed with sodium azide eliminated the contaminating growth and it was decided to extend the project duration until the end of March 1990 without budget changes.

The present report is the final report to the scientific authority Dr. R.G.L. McCready for contract 23440-8-9156/01SQ, SSC file 09 SQ. 23440-8-9156 and reports on all the objectives which were successfully accomplished.

2. MATERIALS AND METHODS

2.1 Biosorbent Production

The biosorbent was produced by Dr. M. Tsezos at McMaster University. A strain of R. arrhizus was grown in a twin 14-L bench top fermentor in a nutrient broth under carefully controlled conditions. Sterile conditions were used to prevent contamination by the microorganisms. The R. arrhizus was separated from the nutrient solution by filtration, was washed thoroughly and autoclaved. The biomass was then freeze-dried. The dried biomass was size classified and immobilized using a proprietary immobilization process to produce particles of 20-25 mesh size. Several batches of biomass were produced and tested to compare the uranium uptake between batches. The uranium uptake of the different batches of biomass was examined before and after immobilization and was found to be consistent.

2.2 Bioleach Solution Processing

The mine process water used in this work was bioleach solutions from the Denison Mines underground bacterial leaching stopes in Elliot Lake, Ontario received in 200-litre drums with an initial pH of about 2.4. The bioleach solution was adjusted close to a pH 4.0 with concentrated NaOH in large 200-litre polymeric feed tanks. It has been shown in literature that pH 4.0 is the optimum pH for uranium biosorption.

For loading elution cycles 1 to 8, the pH 4 settled solution was used as is. For the last cycles, the pH adjusted solution was filtered through a coarse cartridge filter prior to use. The range of concentrations observed for the most significant elements in the received bioleach solution and the

corresponding processed bioleach solution concentrations are listed in Table 1.

TABLE 1
Typical Composition Range of the Mine Water Used
to Supply the Pilot Plant.

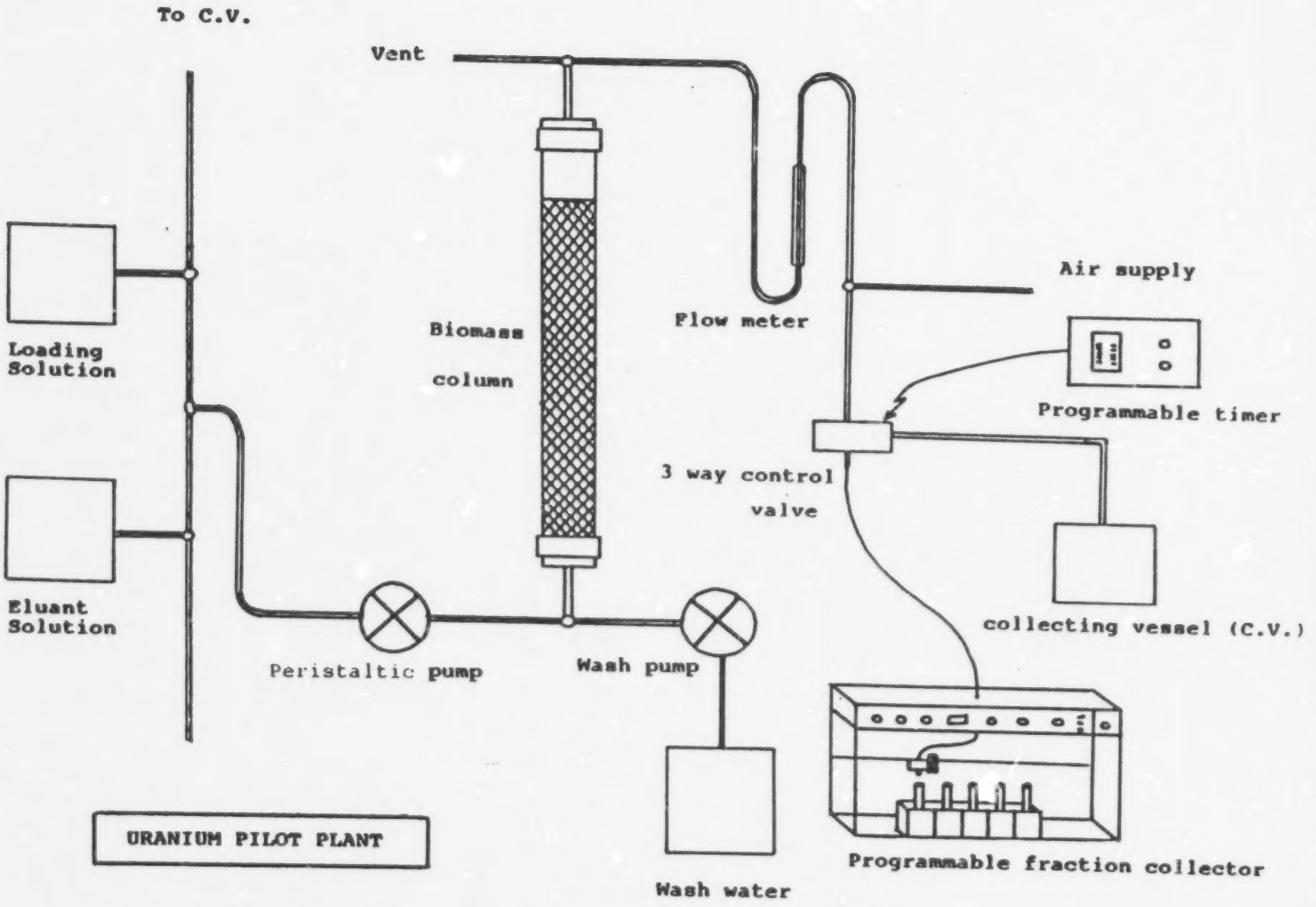
Elements	Concentration range (pH 2.5 bioleach solution) (mg/L)	Concentration range (pH 3.9 bioleach solution) (mg/L)
U	95–160	95–160
Fe	259–550	0.6–7
Ca	200–320	200–315
Mg	13–24	13–23
Si	20–35	20–31
Al	30–55	27–45
Y	8–26	6–21
S	527–880	520–790
Sc	<0.5	<0.5
Th	44–181	0.5–51

The pH of the supplied bioleach solution was in the range 2.4-2.5 and the pH of the processed bioleach solutions was in the range 3.7-4.0.

Generally, at least 85% of Th precipitated during adjustment of solution to pH 4, and, except for one batch of bioleach solution, between 98% and 99.9% of Fe precipitated at the same time. Uranium loss due to pH adjustment was between 0% and 10%. Part of Al, Si, S and Y also precipitated.

2.3 Pilot Plant Characteristics and Operation

The column used in the pilot plant was a 6.4 cm i.d. and 97 cm long transparent acrylic cylinder. The column was loaded with 965 g of biomaterial. The biomaterial was washed with tap water for 60 hours at 6.5


To C.V.
Vent
Loading Solution
Eluant Solution
Biomass column
Flow meter
Air supply
Programmable timer
3 way control valve
collecting vessel (C.V.)
Peristaltic pump
Wash pump
Wash water
Programmable fraction collector
URANIUM PILOT PLANT

Fg 1

ml/min prior to the first loading with pH 4 bioleach solution. Figure 1 presents a schematic diagram of the pilot plant. The biomaterial in the column was loaded with pH 4 bioleach solution in an up flow direction. The average flow rate for the first 11 cycles was 31.0 mL/min (Standard deviation: 1.2 mL/min). Pilot plant effluent samples were taken every 30 min during loading and analyzed for U. Selectively interdispersed samples were also analyzed for Fe, Ca, Mg, Si, Al, Th, Y, S.

The volume of the bioleach solution used to saturate the column varied from 70 L (26 bed volumes) to 350 L (128 bed volumes), depending on the bioleach solution composition.

Following uranium loading, the column was drained and the biomaterial was washed with 22 l of tap water in an up flow direction. After washing, the column was drained again.

The column was then eluted with 25 l of 0.5 N $NaHCO_3$ solution prepared with tap water in an up flow direction. Tap water had the following composition: Ca:18 mg/L, S:8 mg/L, Mg:2.2 mg/L, Si:2.1 mg/L, Al:0.1 mg/L. For the first 4 elution cycles, the average eluant flow rate was 32.0 L/min (Standard deviation: 1.5 mL/min). For elution cycles 5 to 11, the average eluant flow rates was 18.3 mL/min (Standard deviation: 1.7 mL/min). Samples were taken during elution and analyzed for the elements mentioned previously.

At the end of the fifth uranium elution cycle the immobilized biomass was washed with 0.1 N EDTA solution in order to remove accumulated elements from the column. At the end of the eight cycle the pilot plant operation stopped for a few weeks due to interruption in the supply of mine water. During that time the column was contaminated by a bacterial growth. To eliminate the contaminating growth the immobilized biomass bed was

washed with 20 L of 0.1w/w sodium azide solution followed by 19 L of neutral distilled water and 200 L of pH = 3.5 distilled water. The treatment was successful in eliminating the contaminating growth.

2.4 Analytical Methods

2.4.1 Uranium Analysis

Uranium (VI) analysis was carried out at CANMET by the fluorimetry technique. Following are two examples of repeated uranium analysis of two Denison Mines bioleach solution samples adjusted to pH 4.0.

Example 1. U(mg/L): 121, 115, 115, 108, 111, 106, 112, 97, 105, 95, 105, 95, 105, 95, 122, 121, 124; Mean = 111.7 mgU/L; Standard deviation = 8.3%.

Example 2. U(mg/L): 129, 133, 132, 129, 129, 129, 117, 130, 126, 146, 138, 135, 133, 125, 133; Mean = 130.9 mgU/L; Standard deviation = 4.9%.

The standard deviation for the uranium analysis of the pilot plant feed ranged between 4% and 10%. The standard deviation of the uranium analysis for the eluate which contained uranyl carbonate complexes was better than 13%. Thorium, Yttrium, Scandium and other rare earths were analysed by HPLC (High Pressure Liquid Chromatography). For Th and S, the highest standard deviation calculated was 2% from the analysis of 3 samples repeated 5 times. For Y, rare earths and Sc, the highest standard deviation was 5%.

Fe, Ca, Mg, Si, Al and P were analysed by the ICP (Inductively Coupled Plasma) method. The standard deviation was better than 5%.

Na was analysed by Atomic Absorption Spectroscopy.

Immobilized biomass particle samples were analyzed for U, Fe, Ca, Mg, Si, Al, Th, Y, P, Na, Sc following digestion in concentrated acid.

3. RESULTS AND DISCUSSION

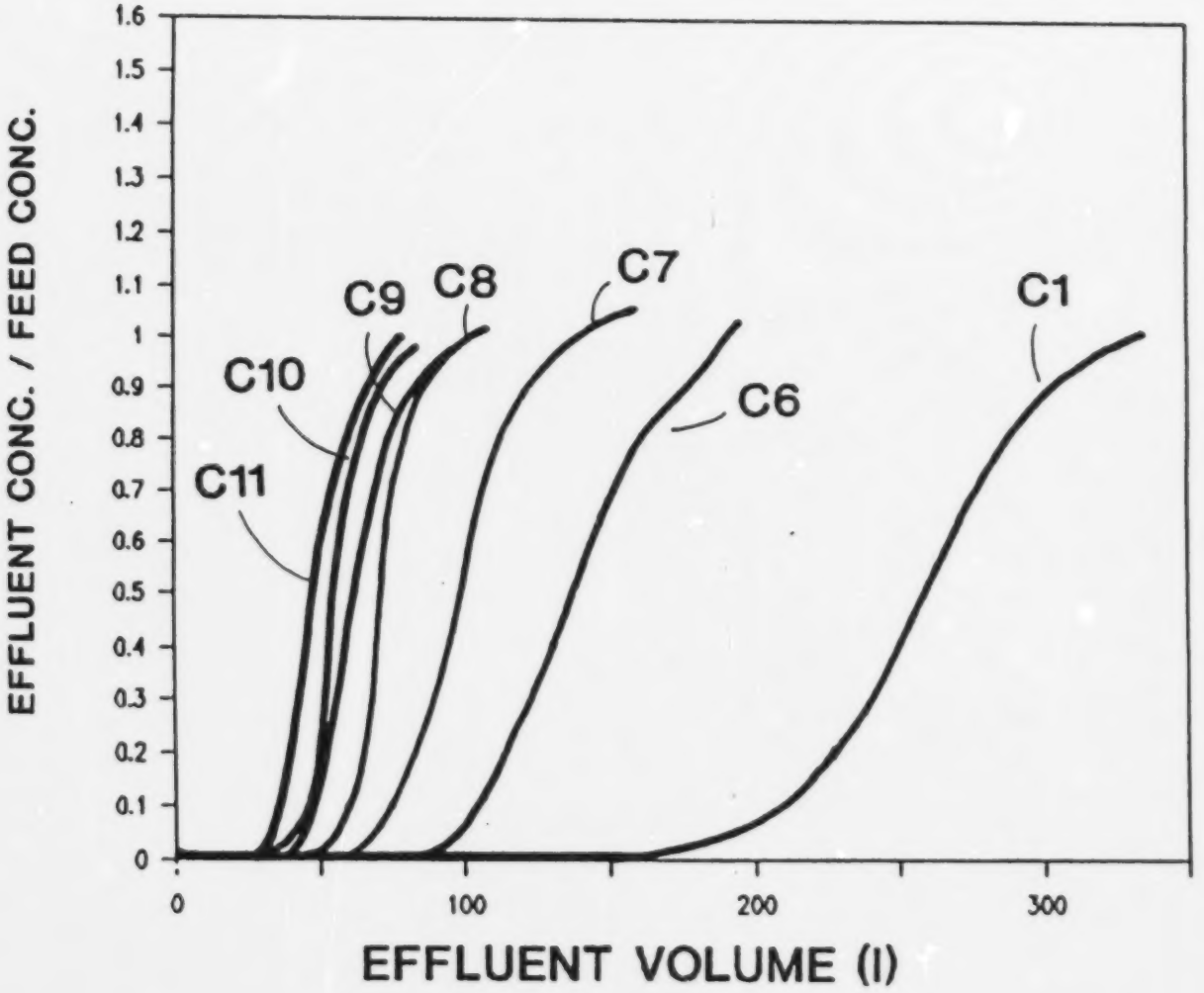
3.1 Uranium Sequestering Results

3.1.1 Uranium Loading

Uranium was selectively removed with 100% efficiency from the mine solution in all 16 cycles. The uranium uptake breakthrough curves were similar to those experienced and reported for the mini pilot plant that was operated by Dr. M. Tsezos at McMaster University earlier. The biosorptive breakthrough curves also showed a consistent narrow biosorption zone suggesting favourable kinetic properties for the immobilized biomass particles. A cummulative plot of the first 11 uranium breakthrough curves is shown on Figure 2. The feed solution uranium concentration was not constant among the various shipments of mine water. Therefore either the total weight of uranium loaded on the immobilized biomass bed or the biomass uranium uptake capacity of the immobilized biomass during each uranium biosorption cycle are the appropriate parameters to use in order to assess the pilot plant performance. Figure 3 summarizes the total uranium adsorbed by the column during each cycle for the first 11 cycles.

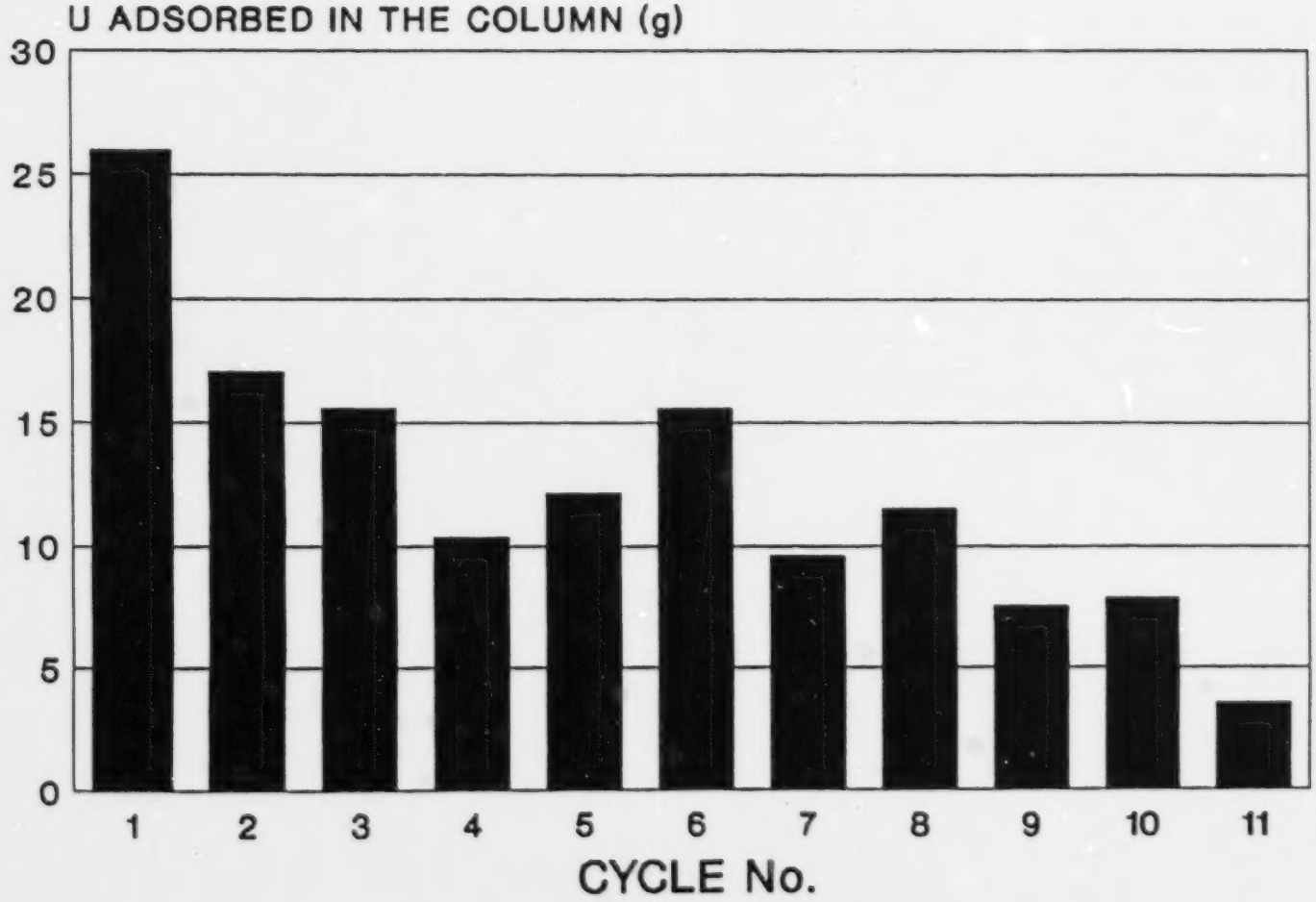
The data on Figure 3 suggest that an initial drop in the uranium uptake capacity is observed in the same way as in the previous mini pilot plant work. Subsequently the total biomass bed uranium uptake ranges between 10 g and 8 g for the next 6 cycles (cycles 4 to 10) exhibiting perhaps a slow gradual decline. The increase in the total adsorbed uranium observed during cycle 6 is interpreted as the result of the removal of some Fe and Al by the EDTA wash of the bed at the end of cycle 5. This is supported by the information in Table 2 which summarizes the metal content of the immobilized biomass particles before and after the EDTA wash, showing a substantial reduction in Fe and Al content.

LOADING BREAKTHROUGH CURVES



Fg 2

WEIGHT OF URANIUM LOADED IN THE COLUMN



Fg 3

TABLE 2

Effect and EDTA Wash on Immobilized Biomass

Particles Elemental Composition

Immobilized Biomass Particles Elemental Composition	Before EDTA Washing	After EDTA Washing
U (%)	0.02	0.02
Fe (%)	1.10	0.45
Ca (%)	0.10	0.05
Mg (%)	0.02	0.01
Si (%)	0.01	0.01
Al (%)	0.40	0.81
Th (%)	0.03	0.03
Y (%)	0.01	<0.005
Na (%)	0.13	0.02

Table 3 summarizes the biomaterial uranium, iron and aluminum content at the end of each of the first 10 cycles for samples taken from the top of the column. The biomass aluminum content increases rapidly during the first three cycles and then remains close to an equilibrium value of 1%. The iron content increases gradually up to cycle 4 to a value of about 0.4%. From cycle 6 on, the iron content remained close to an equilibrium value of about 0.4%. All other elements remained at low levels. The bottom of the column biomaterial however exhibited a substantially different picture.

Table 4 summarizes the difference in the immobilized biomass metal content between samples taken from the top and the bottom of the column, at the end of the uranium loading for three selected cycles. From the results summarized in Table 4 it is apparent that for the mine water under consideration and by the fifth cycle, the aluminum and iron content of the bottom section of the immobilized bed had reached an equilibrium value. The corresponding biomass uranium uptake capacity arrived to a new

TABLE 3

Metal Content of Immobilized Biomass Particles from Top of Column for the First 10 Cycles of Operation

Cycle No.	Metal Content (%)		
	U	Fe	Al
1	6.0	0.01	0.1
2	3.4	0.2	0.6
3	3.9	0.2	1.1
4	3.6	0.4	1.4
5	3.8	0.6	1.2
6	2.9	–	–
7	3.3	0.3	1.0
8	2.9	0.4	1.1
9	3.2	0.3	0.9
10	2.8	0.4	1.0

equilibrium value in the range of 1.6% to 2%. The thorium accumulation by the biomass, however, continued to increase from cycle 5 on. Between the fifth and tenth cycle the biomass thorium content increased at the top of the column by an order of magnitude (from 0.05% to 0.5%) while it had reached perhaps an equilibrium capacity of about 3.6% or 4% at the bottom of the column.

TABLE 4

Summary of Biomass Metal Content Top and Bottom of Column

Element	End of U Loading Cycle 5		End of U Loading Cycle 8		End of U loading Cycle 10	
	Top	Bottom	Top	Bottom	Top	Bottom
U (%)	3.8	1.6	2.9	1.6	2.8	2.0
Fe (%)	0.6	5.2	0.4	3.4	0.4	3.2
Al (%)	1.2	0.2	1.1	0.5	1.0	0.2
Th (%)	0.05	3.6	–	–	0.5	4

3.1.2 Uranium Elution

Uranium elution was complete and efficient in all elution cycles irrespective of eluant flow rate. Figure 4 summarizes the observed uranium elution efficiency for the first 11 cycles. The eluate uranium concentration profile was always narrow and sharp. Individual uranium elution concentrations profiles are summarized in the Appendix. The volume of eluant required to elute the adsorbed uranium can be further optimized so that the uranium concentration of the eluate, as well as its purity, can be increased further. It is possible to recover the entire adsorbed uranium in a small fraction of the presently used eluant thus producing uranium eluate concentrations perhaps four times higher than those presently observed. With the presently employed elution practice, a peak eluate uranium concentration of up to 14 g/L was observed while 10 g/L was an average for most cycles (Figure 5).

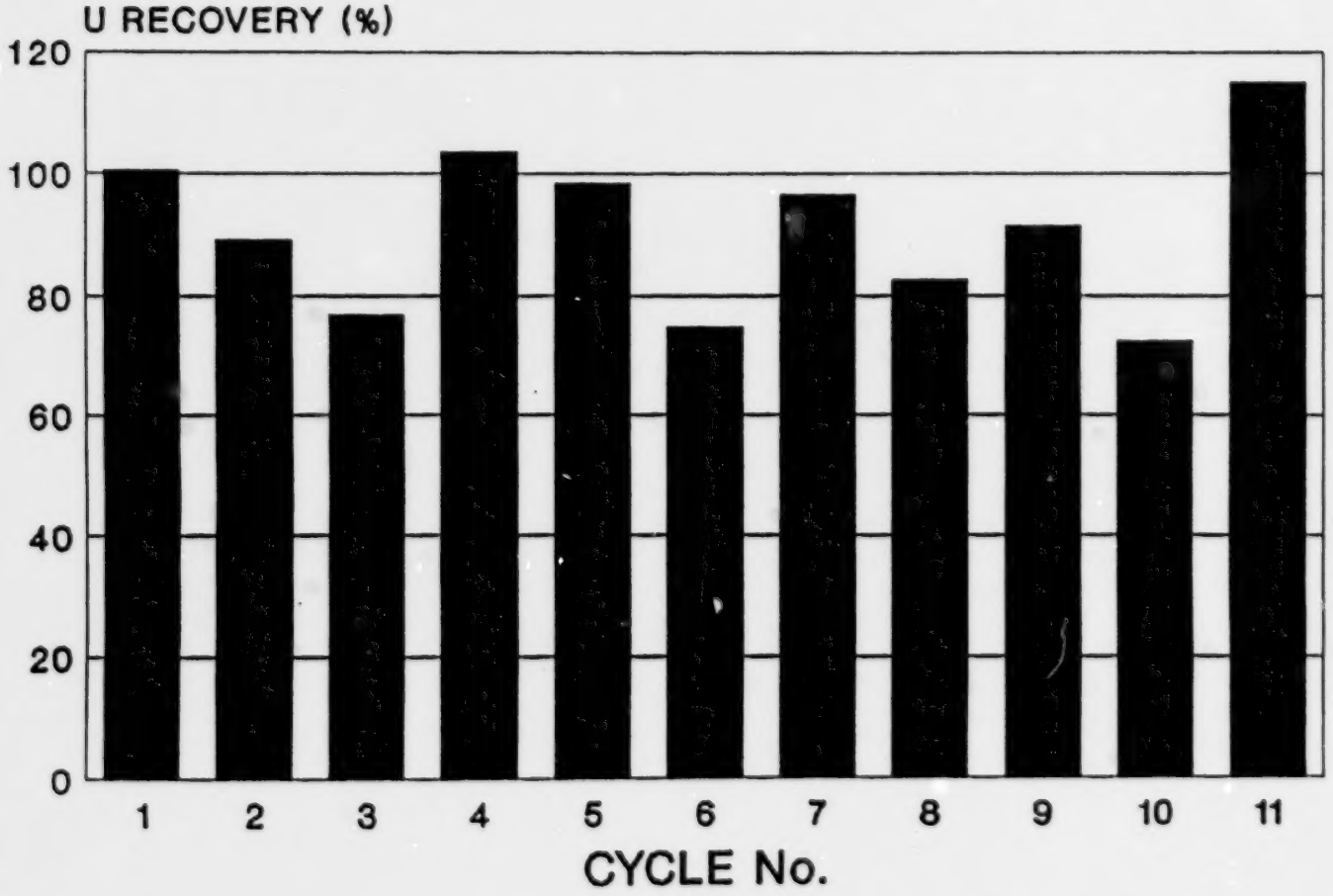
3.2 Behaviour of Other Elements

The monitoring of the behaviour of the other elements listed in earlier sections of the present report led to several interesting conclusions. The behaviour of the most significant elements is discussed in the following section.

3.2.1 Aluminum

Aluminum presented characteristic loading curves similar in shape to those of uranium but indicative of a substantially lower uptake capacity evidenced by early breakthrough. The data from Tables 3and 4 suggested that the immobilized microbial biomass aluminum uptake capacity reaches

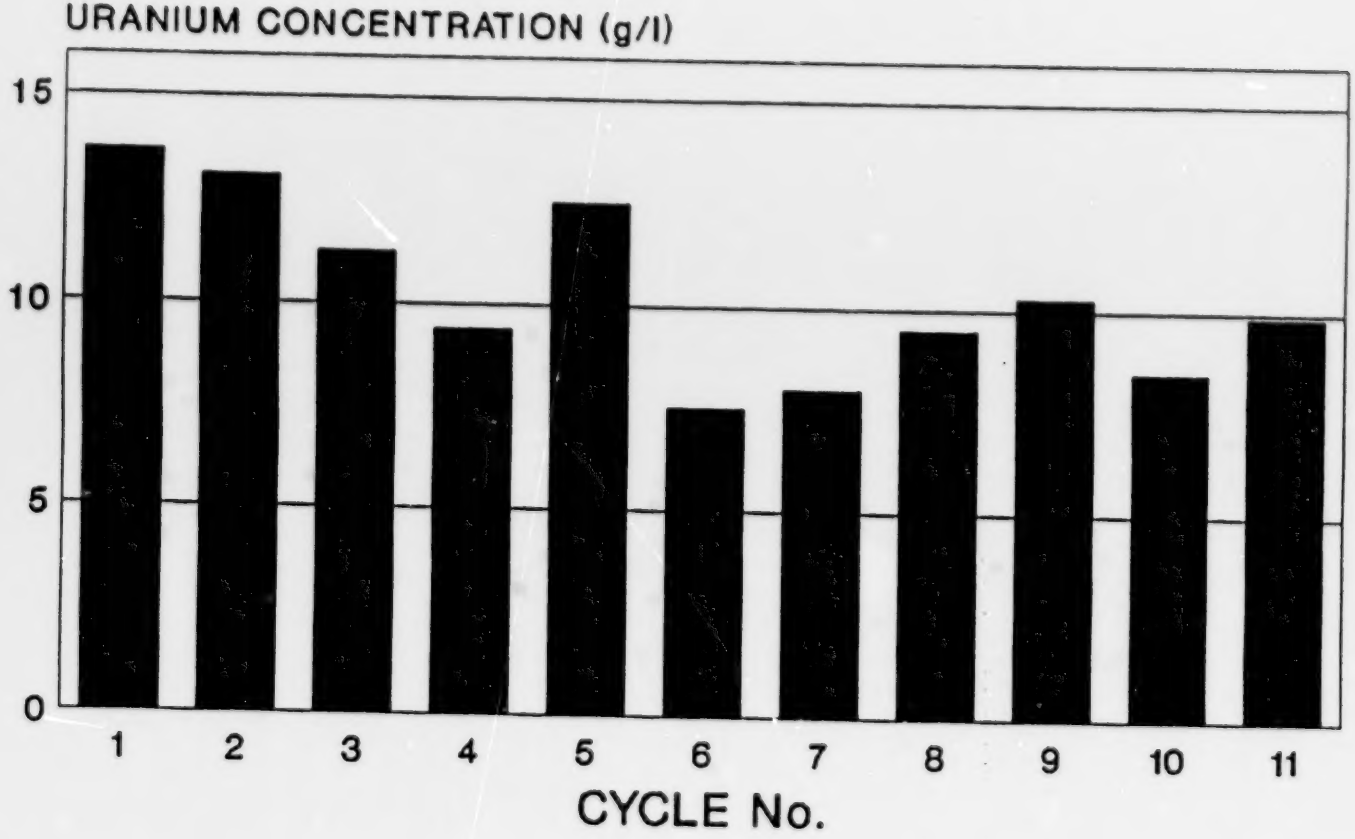
ELUTION U RECOVERY



Fg 4

U PEAK CONCENTRATION

Elutions 1 to 11



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equilibrium, throughout the entire column length, by the third cycle. The corresponding aluminum loading averages about 1% of the biomass weight. Examples of characteristic aluminum breakthrough curves are shown in Figures 6 to 8 for typical cycles.

During elution only part of the adsorbed aluminum was eluted. Typical aluminum elution curves are shown in Figures 9 to 11. The important characteristics of aluminum elution was that it eluted partly and very early during the elution part of each cycle requiring only a very limited volume of eluant.

3.2.2 Iron

Iron was adsorbed by the immobilized microbial biomass particles. The behaviour of iron was predictable and has been discussed by Tsezos et al[1] in detail in literature. Iron reached an adsorption level of about 0.4% at the top sections of the column by the fourth cycle. The bottom section of the column, however, suggested a significantly higher iron content exceeding 3%. The high adsorptivity of the iron hydrolysis species and the upflow mode of column operation can explain these results.

During elution, iron was not removed from the column as illustrated for example on Figures 9 to 11. As expected, elution of iron with the sodium bicarbonate solution (at an alkaline pH) was not observed.

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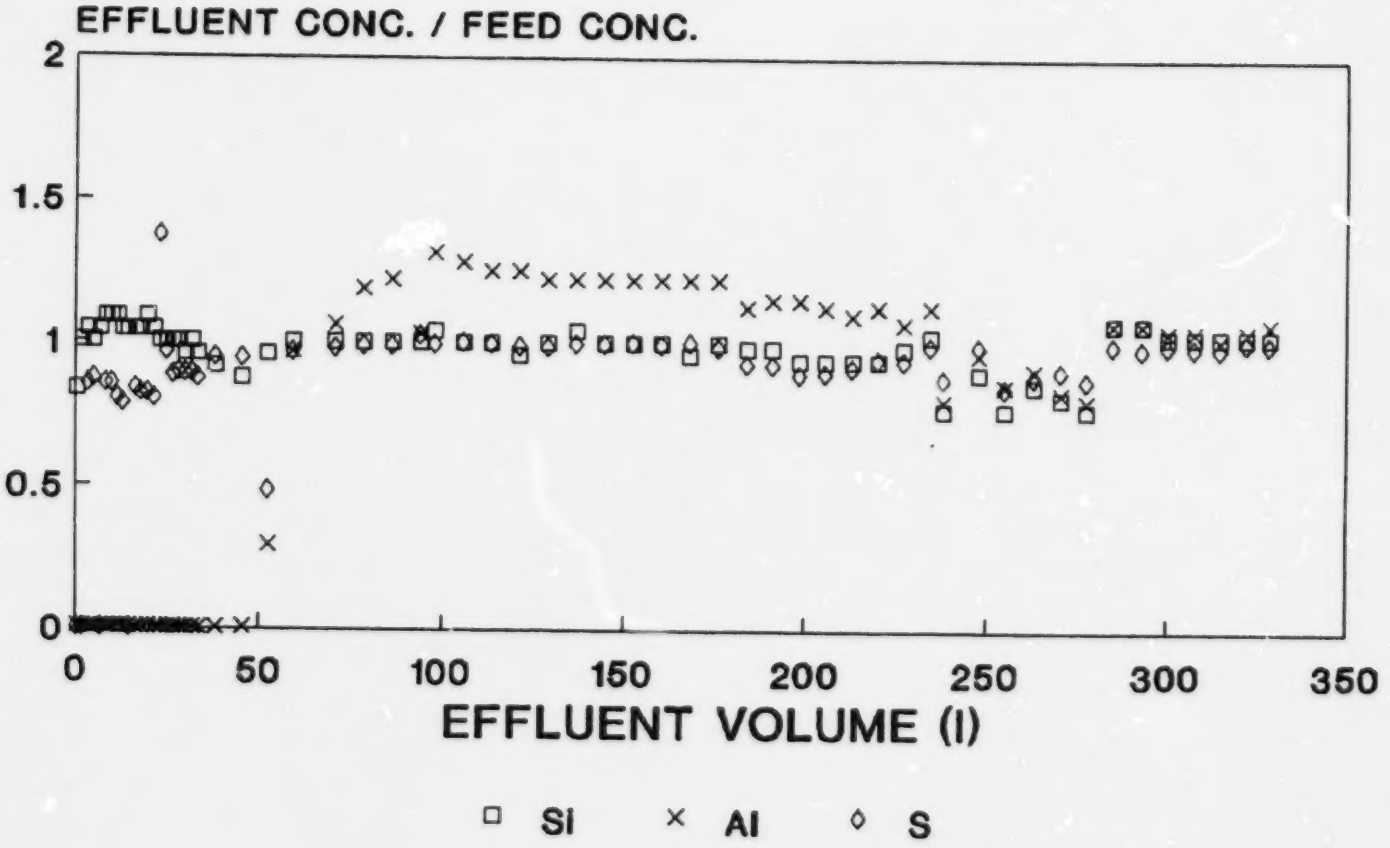
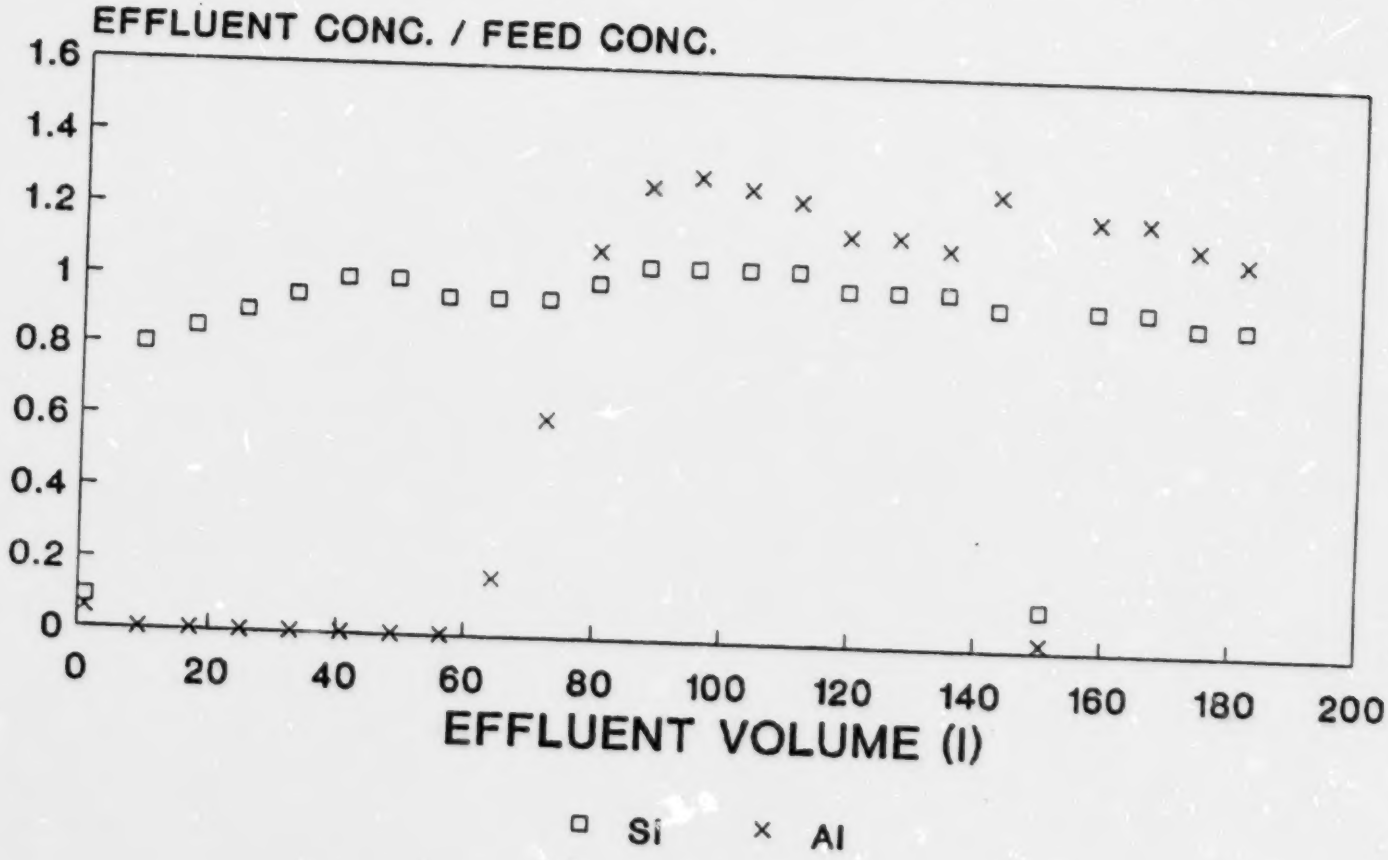
1 Tsezos, M. and Mattar, S., Talanta, 33, 3, pp. 225-232, 1986.

LOADING BREAKTHROUGH CURVES
(Cycle 1)



Fg 6

LOADING BREAKTHROUGH CURVES
(Cycle 4)



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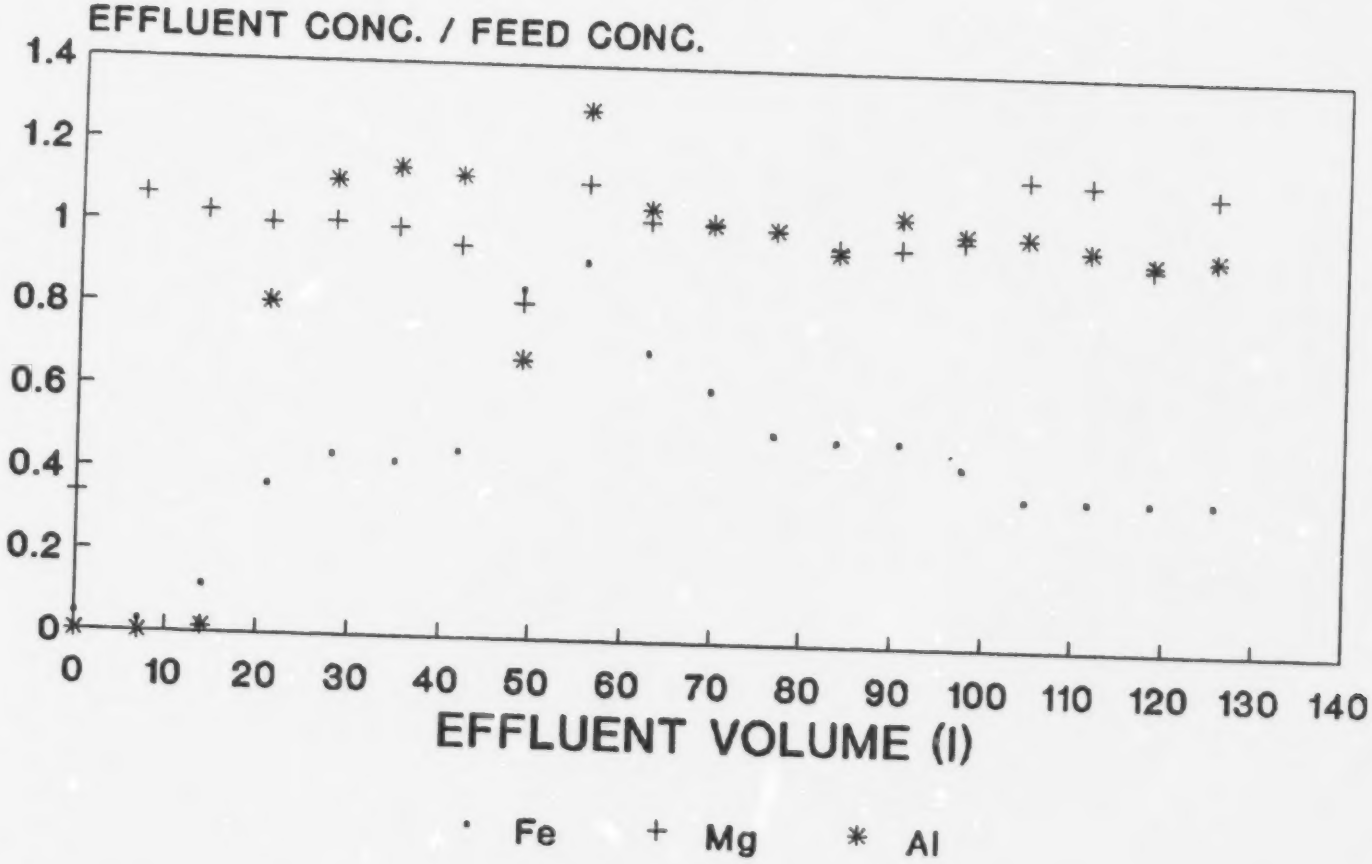
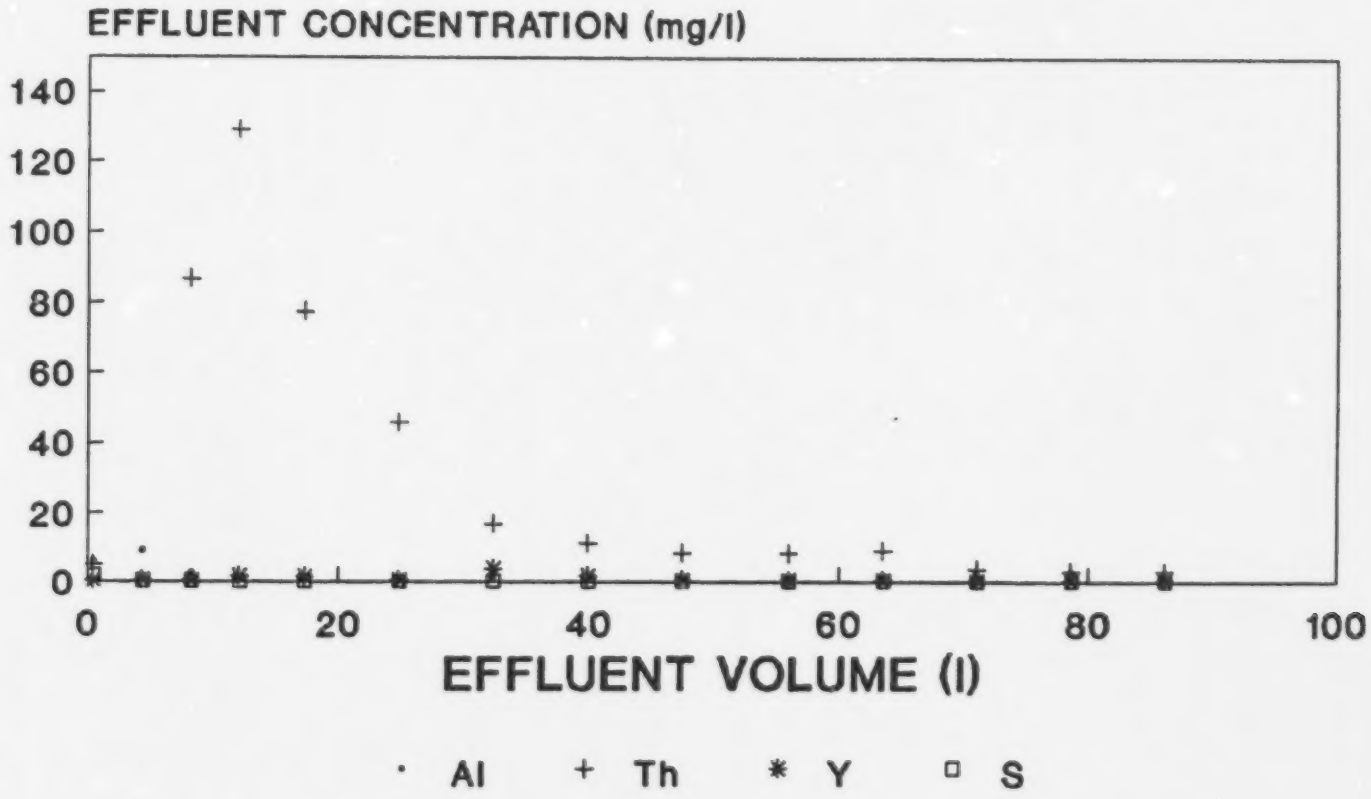
LOADING BREAKTHROUGH CURVES
(Cycle 10)



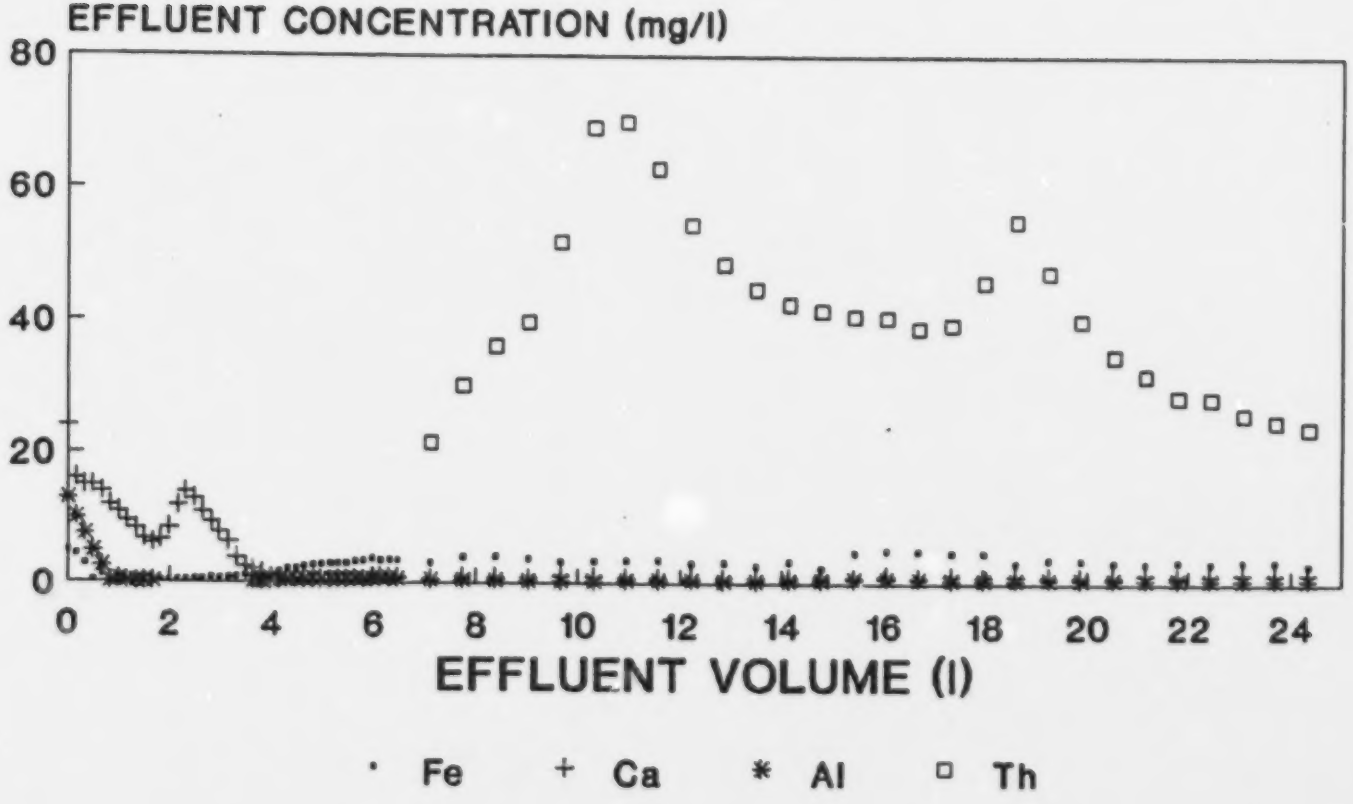
Fg 8

ELUTION 1
Al - Th - Y - S



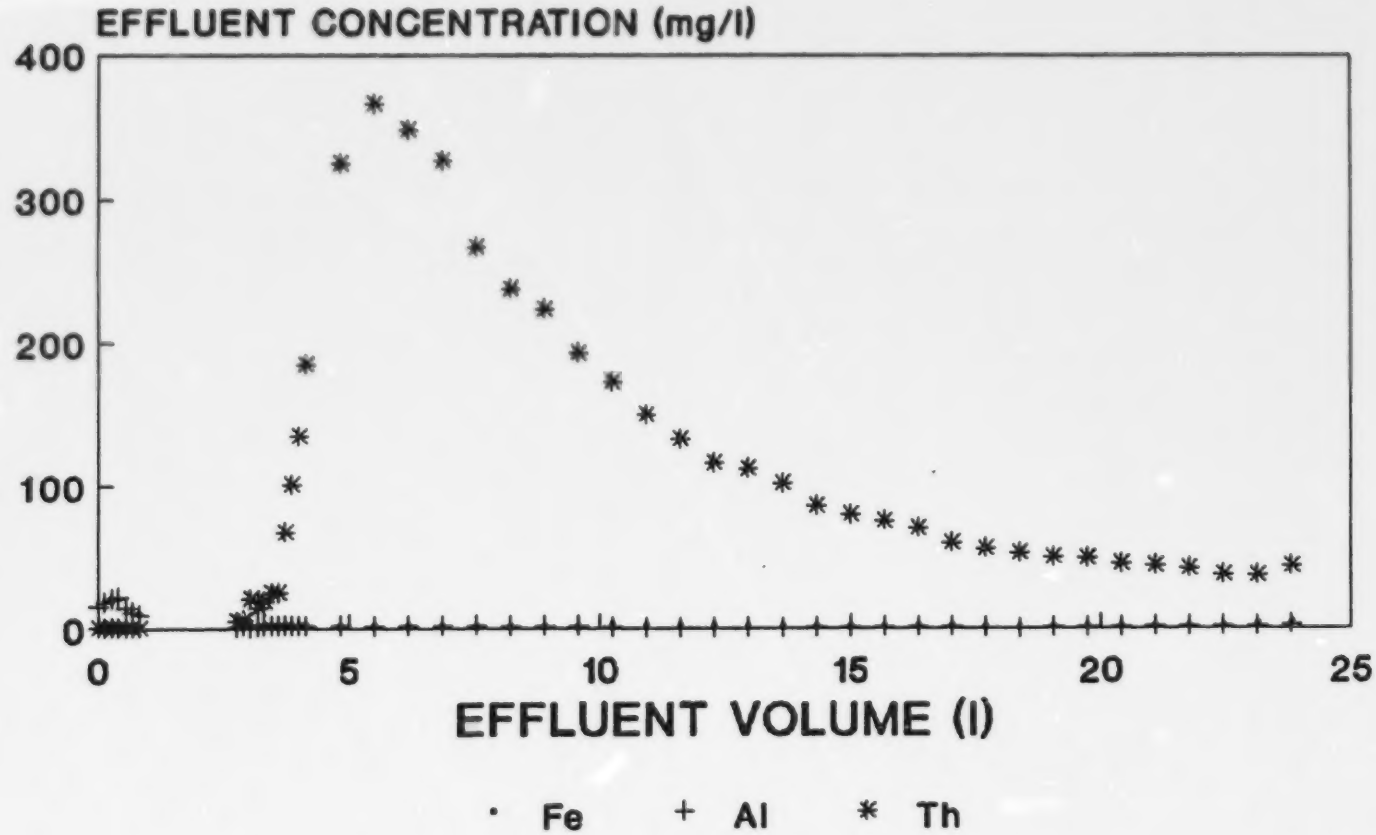
Fg 9

ELUTION 5
Fe - Ca - Al - Th



Fg 10

ELUTION BREAKTHROUGH CURVES
(Cycle 8)



Fg 11

3.2.3 Thorium

Thorium has been shown in literature to accumulate in the microbial biomass. The detailed mechanistic study of thorium biosorption by Tsezos et al[2] has suggested that the thorium biosorption site is different than that of uranium and that it is preferentially biosorbed at the outside of the fungal cell wall. Looking at the data summarized on Table 4, we see that the bottom of the column was saturated with thorium by the fifth loading cycle to a level of 3.6% to 4%. Typical thorium biosorption breakthrough curves are shown on Figures 12 to 14 and suggest that thorium was removed completely by adsorption from the feed solution. Looking at the data of Table 3 and 4 we can see that by the end of the fifth cycle, the top section of the column has a thorium loading of about 0.05%. By the end of the tenth cycle the top of the column has reached a thorium content of an order of magnitude higher (0.5%). This is indicative of a gradually moving upwards thorium wave that is proposed as responsible for the gradual decrease of the immobilized biomass uranium uptake capacity. Electron micrographs with corresponding microprobe analysis from a different project confirm the abundant presence of iron and thorium in the microbial biomass (Figure 15) and support further the above conclusions.

During elution and under the implemented elution conditions, thorium was eluted partially and at a later time than uranium was as seen on Figures 9 to 11. This difference in elution behaviour provides the opportunity for the separation of thorium from uranium which eluates earlier from the immobilized biomass biosorption column. General radioactivity scans of the

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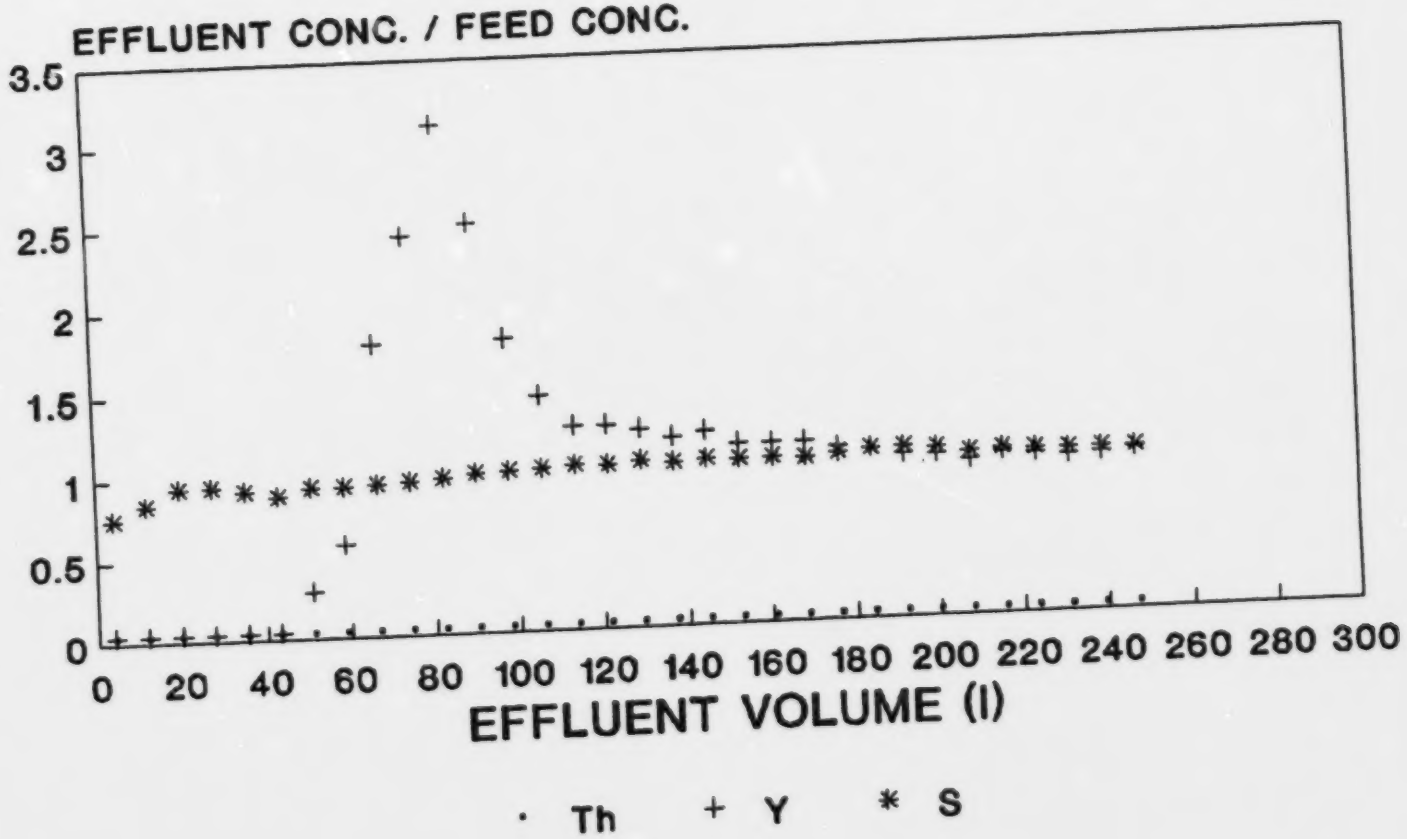
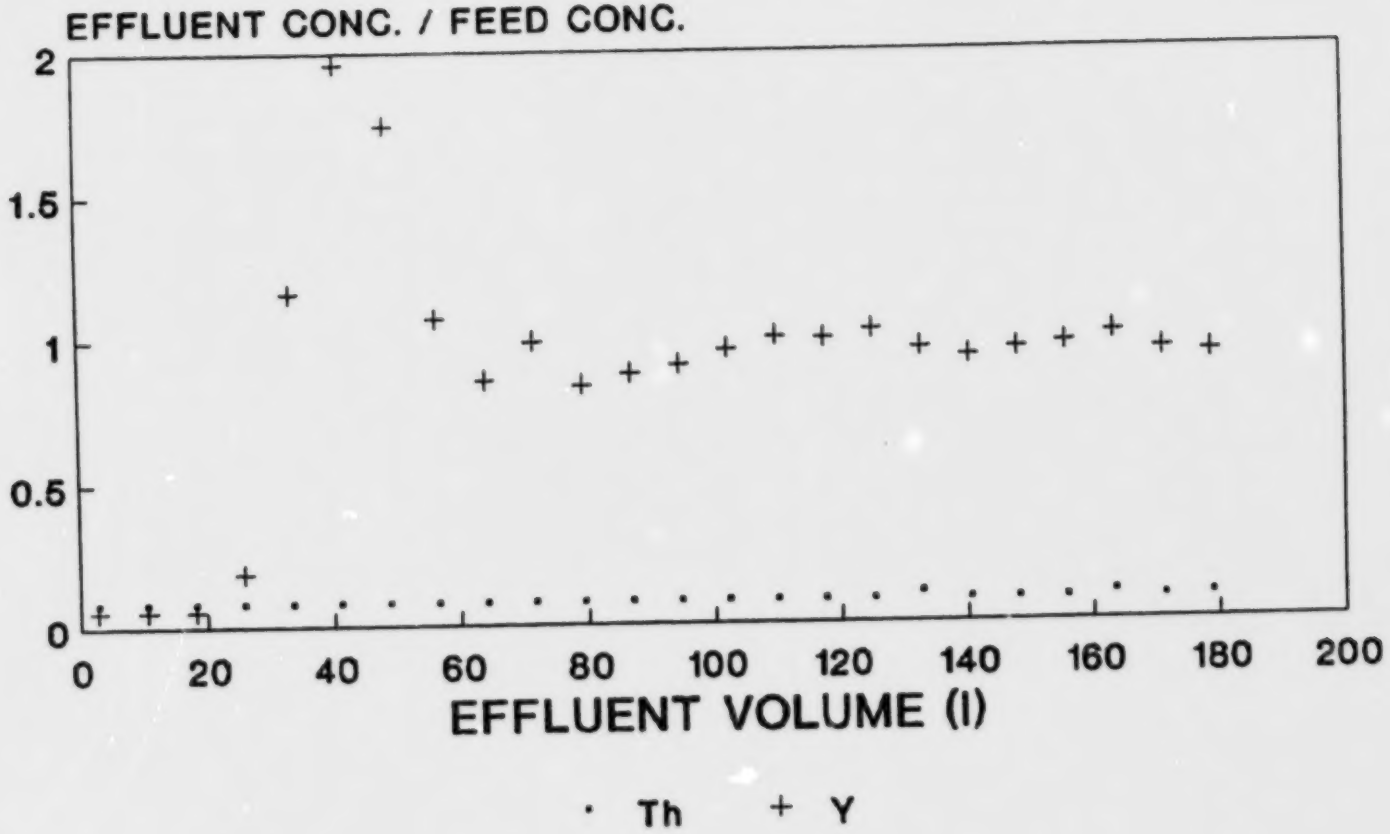
2 Tsezos, M. and Volesky, B., Biotechnology and Bioengineering, 23, pp. 583-604, 1981.

LOADING BREAKTHROUGH CURVES
(Cycle 2)



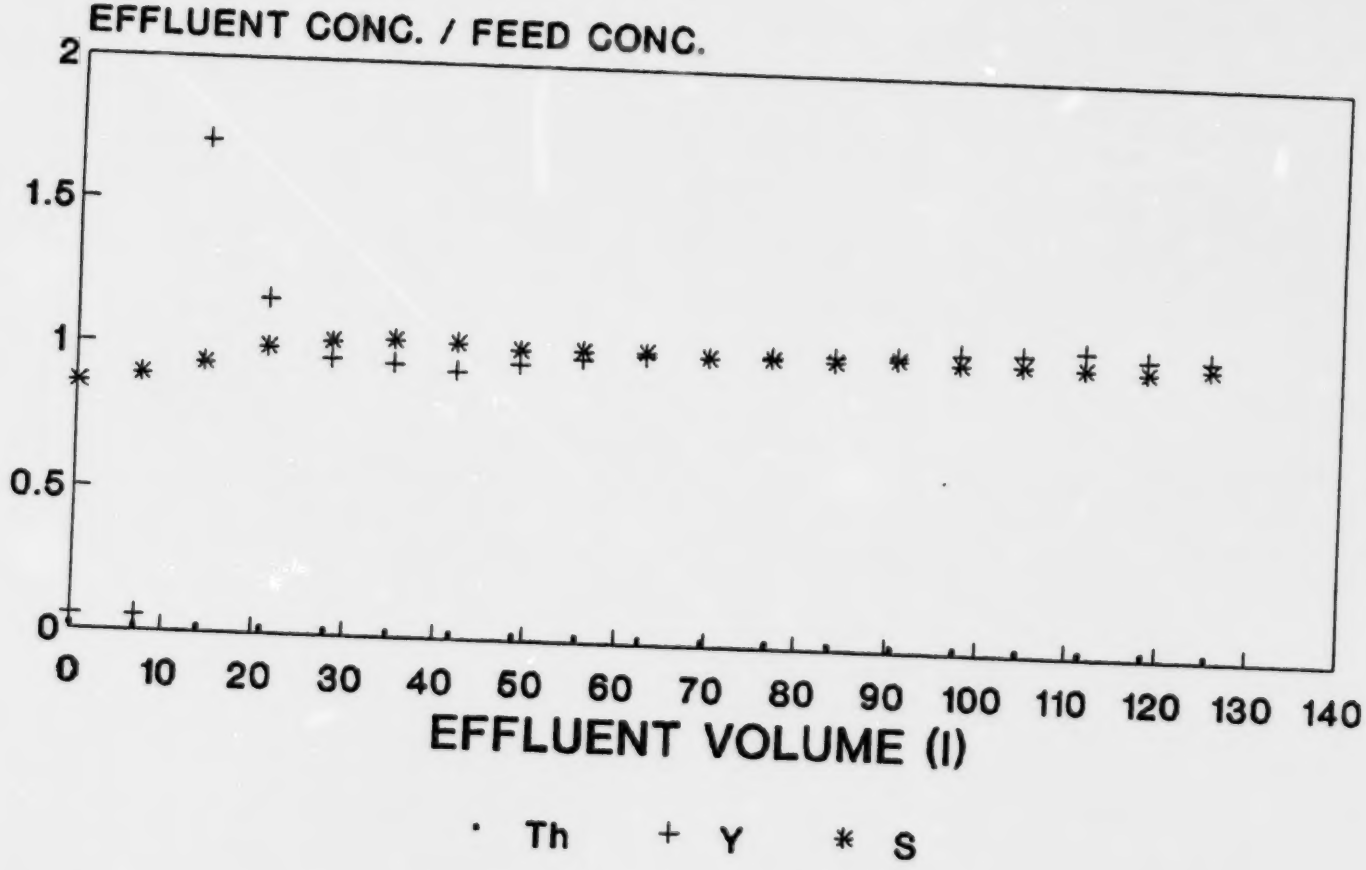
Fg 12

LOADING BREAKTHROUGH CURVES
(Cycle 7)



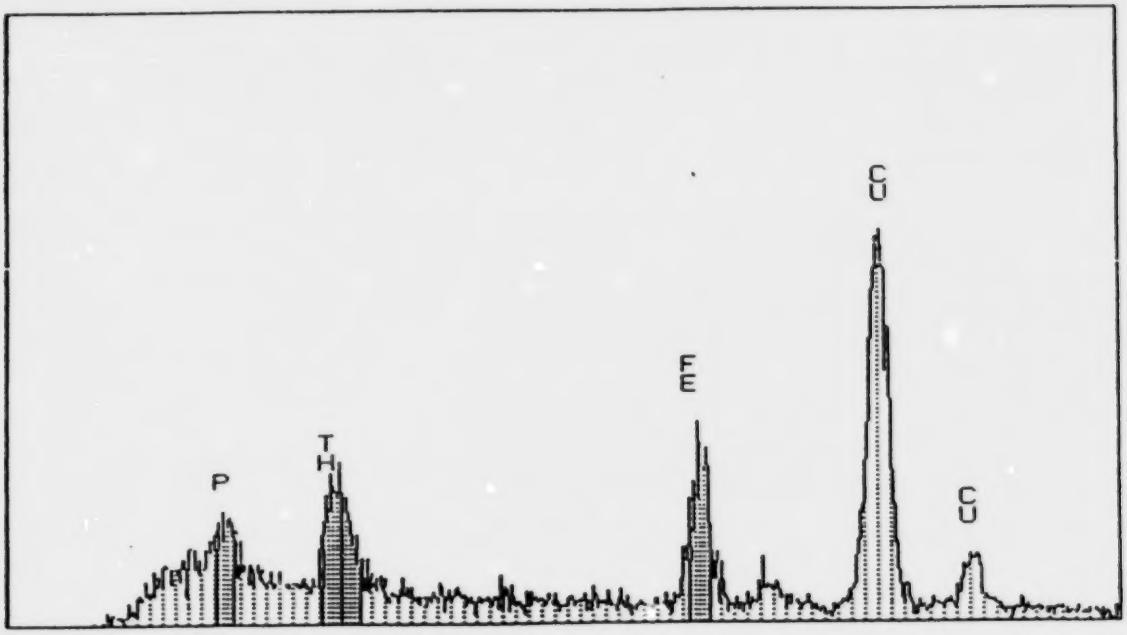
Fg 13

LOADING BREAKTHROUGH CURVES
(Cycle 10)



Fg 14

FIGURE 1



X-ray Energy Dispersion Analysis spectrum of immobilized R.arrhizus was recorded from a pilot plant at the end of an elution cycle after about a year of continuous use as a uranium recovery agent from Denison Mines bioleachate. Spectrum was recorded from the middle of a R.arrhizus cell wall, located near the outer edge of the immobilized biomass particle. The strong (above background) presence of thorium and iron are evident.

column at different heights also support the above hypothesis (Figures 16 and 17).

3.2.3 Yttrium

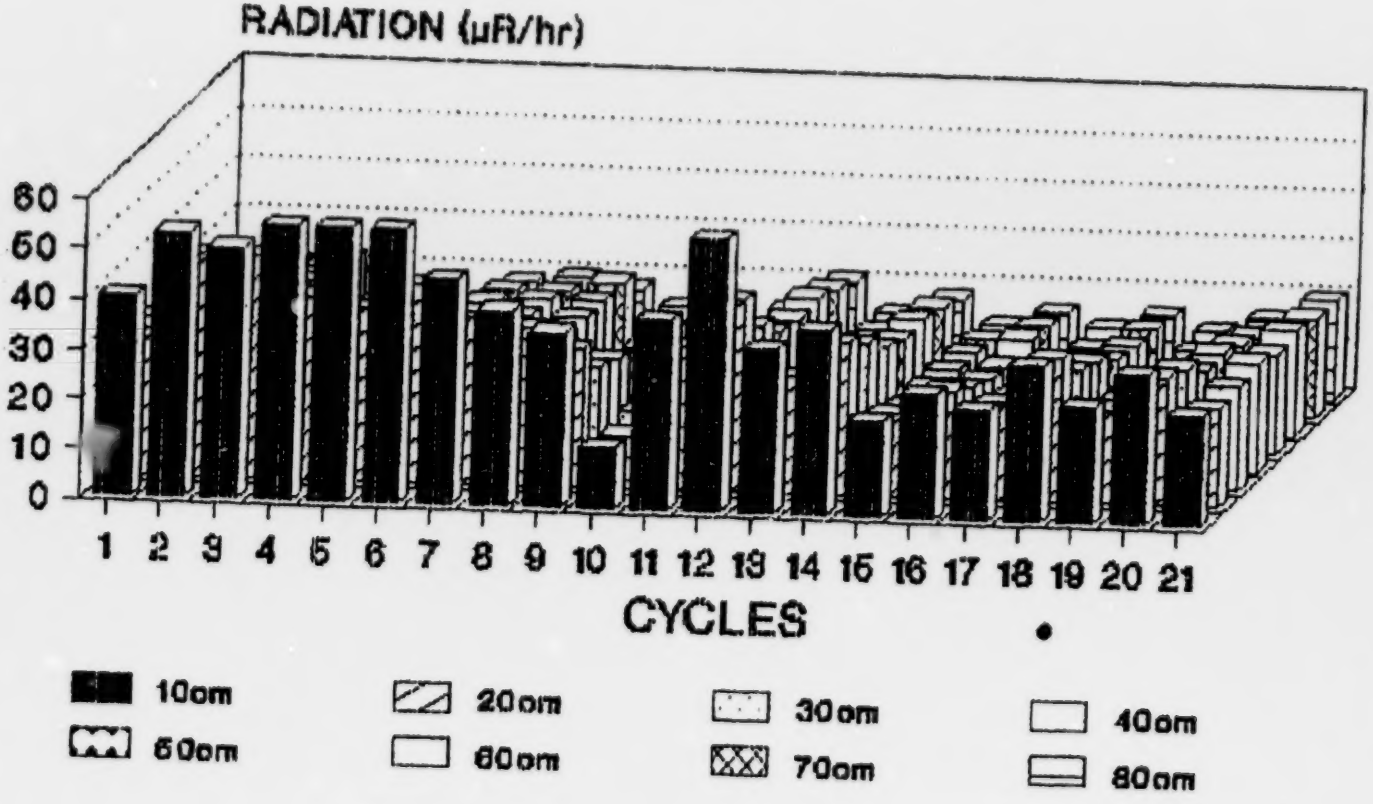
Yttrium was retained initially by the immobilized biomass and was subsequently displaced by the reactor influent presenting characteristic breakthrough curves such as those shown in Figures 12 and 13. The substantial advantage of such behaviour is that yttrium like other rare earths, can be separated from coexisting uranium and thorium by using an immobilized biomass biosorption reactor such as the one used in the present work.

4. CONCLUSIONS

The results from the present work lead to the following conclusions:

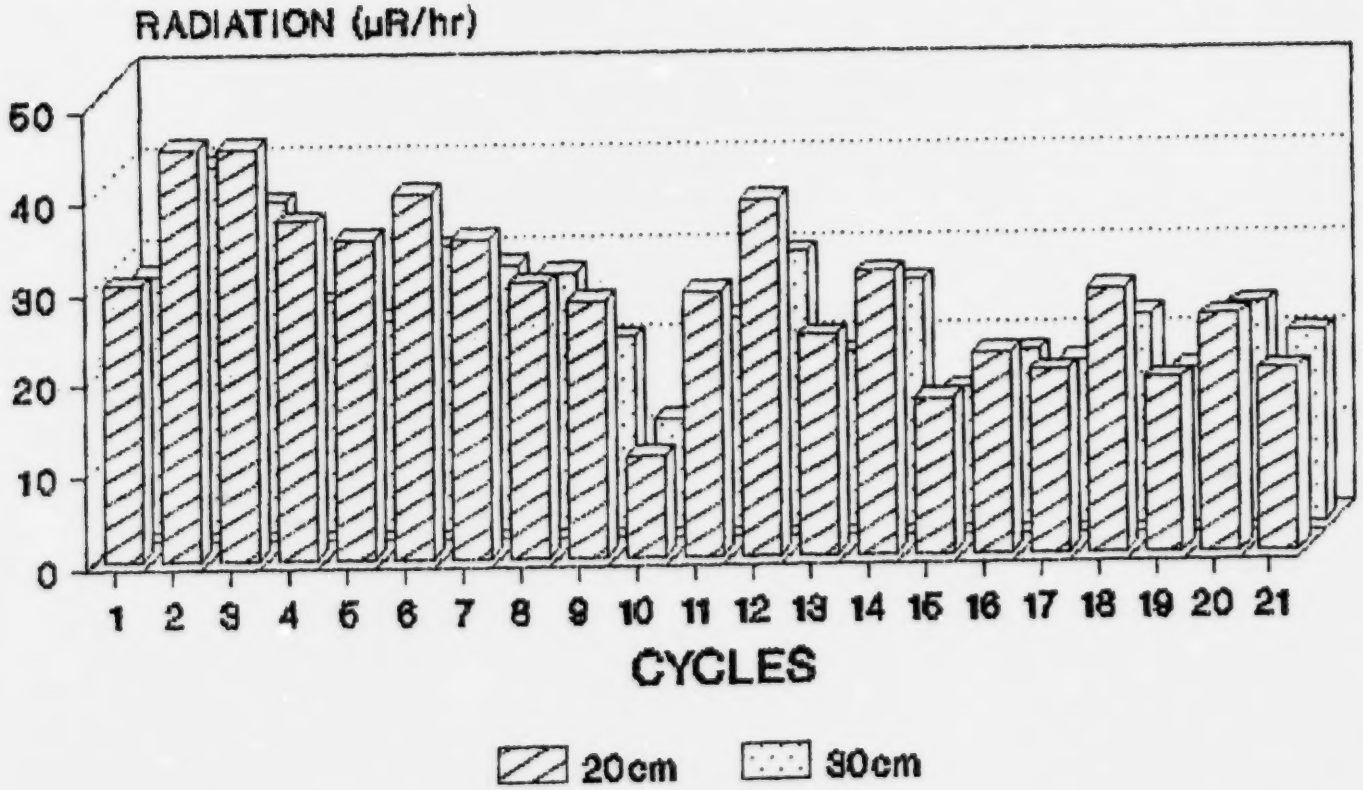
1. The supplied immobilized biomass particles retain their physical integrity and characteristics for extended periods of use (exceeding one year).
2. The supplied immobilized biomass particles retain their favourable kinetic (rate) properties for extended periods of use (exceeding one year).
3. The immobilized biomass particles can efficiently and selectively extract and quantitatively recover uranium from dilute complex solutions.
4. The immobilized biomass particles uranium uptake capacity is affected during the first four cycles by the presence of aluminum and iron. The uranium uptake capacity subsequently stabilizes to a new lower value. This result confirms the previous mini pilot plant results.

RADIATION PROFILE
(ALL CYCLES)



Fg 16

RADIATION PROFILE
(ALL CYCLES)

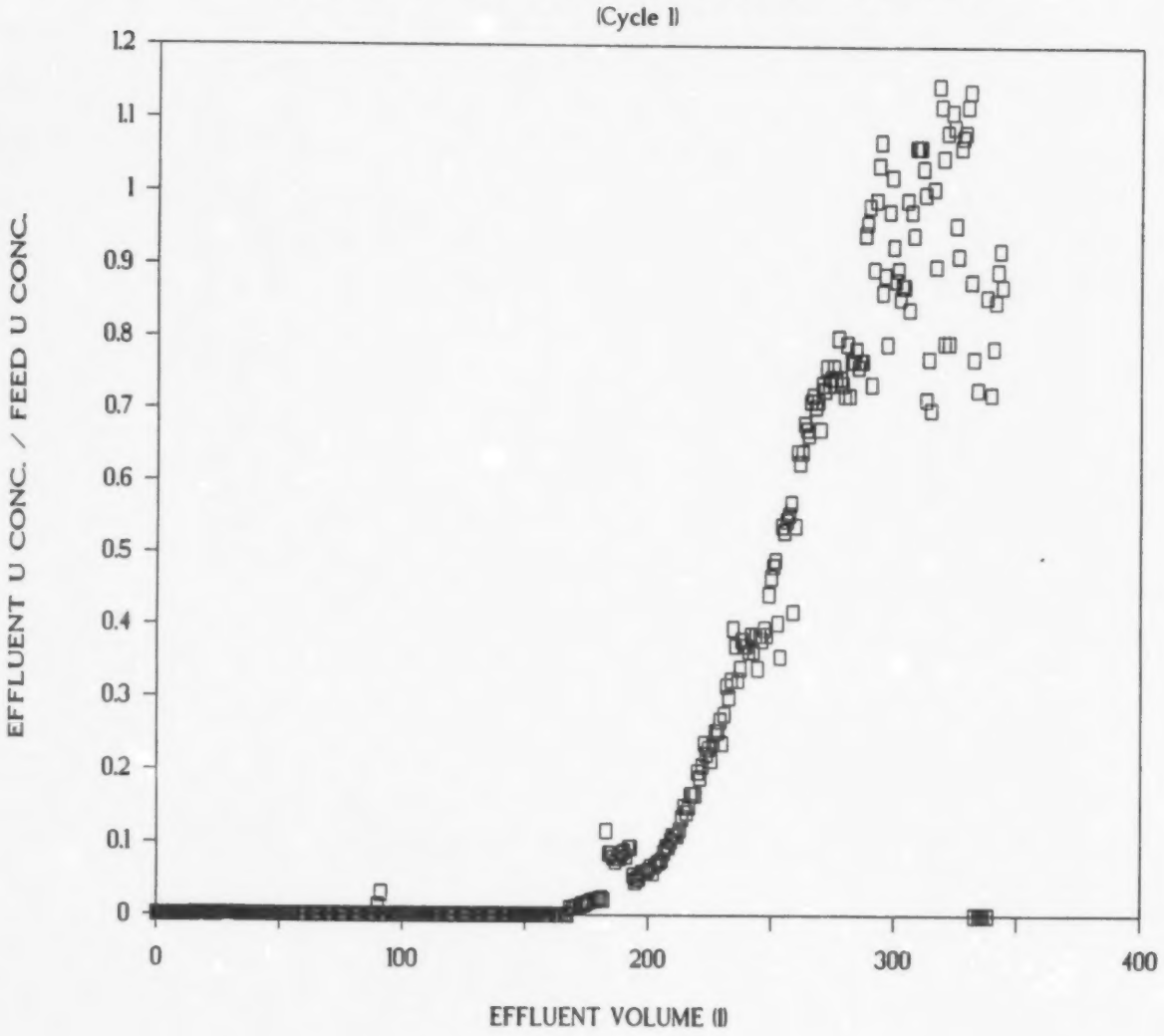


Fg 17

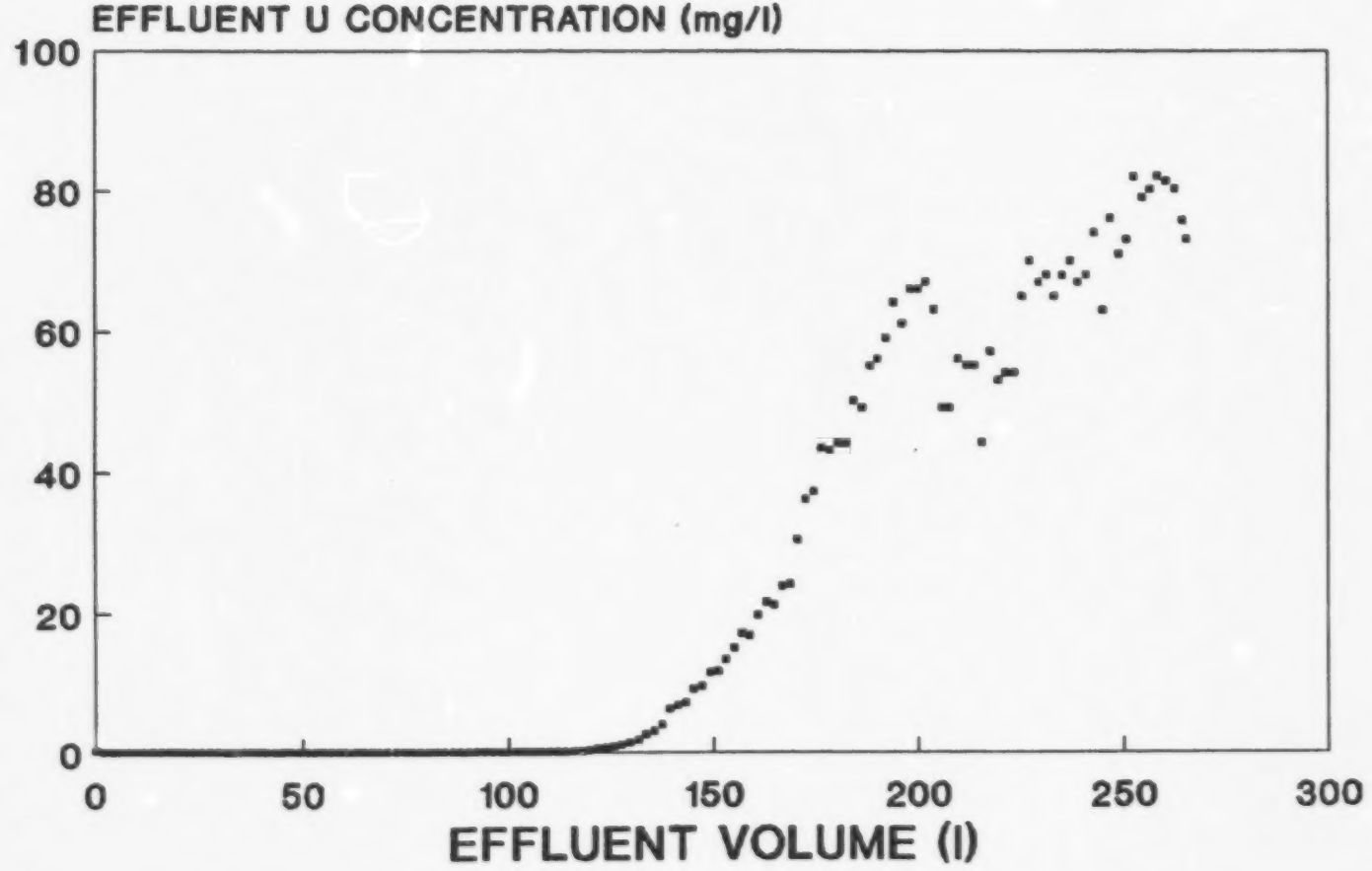
5. Thorium also competes with uranium and reduces the uranium uptake capacity.
6. Adsorbed aluminum, thorium and uranium can be separated during elution as they elute at different times.
7. The supplied immobilized biomass particles can also be used to separate yttrium and rare earths from complex weak solutions.
8. This biosorptive technology is characterised by high selectivity and could provide answers to
   (i) Radioactive waste water treatment
   (ii) Extraction and recovery of elements such as uranium and thorium.
   (iii) Separation of yttrium and rare earths from complex weak industrial solutions for the purpose of recovery.

APPENDIX 1

LOADING BREAKTHROUGH CURVE



LOADING BREAKTHROUGH CURVE
(Cycle 2)



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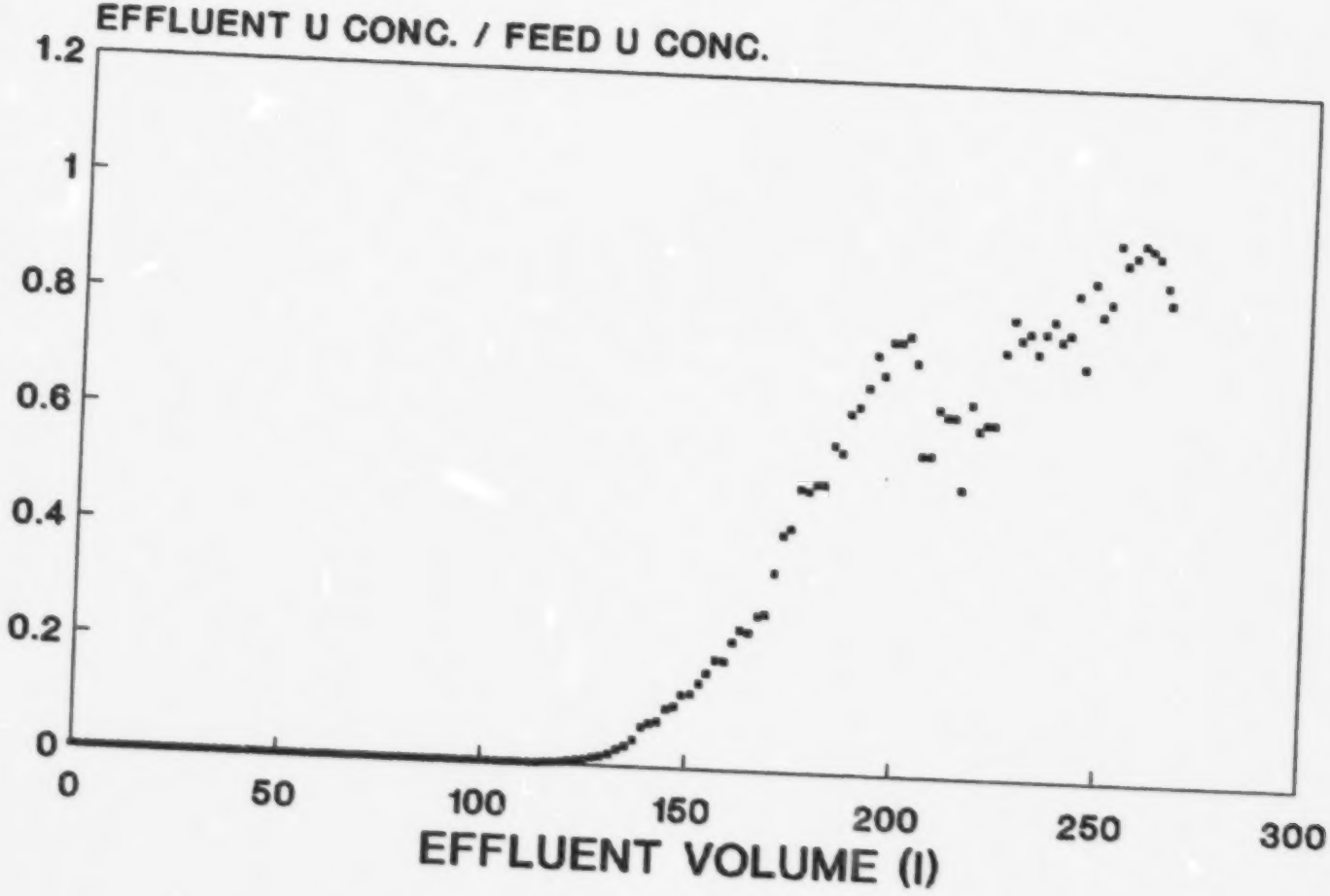
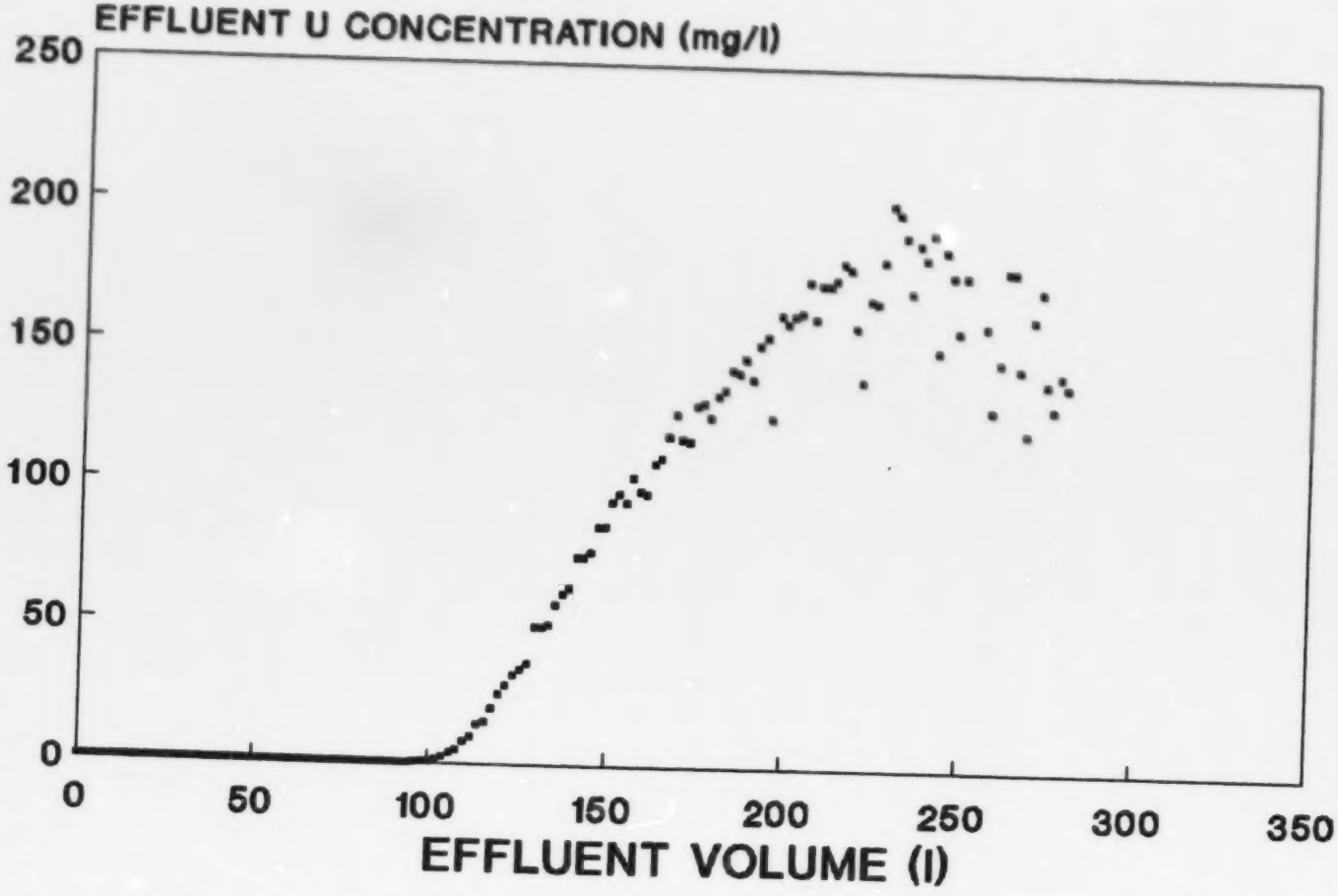
(Cycle 2)



LOADING BREAKTHROUGH CURVE
(Cycle 3)



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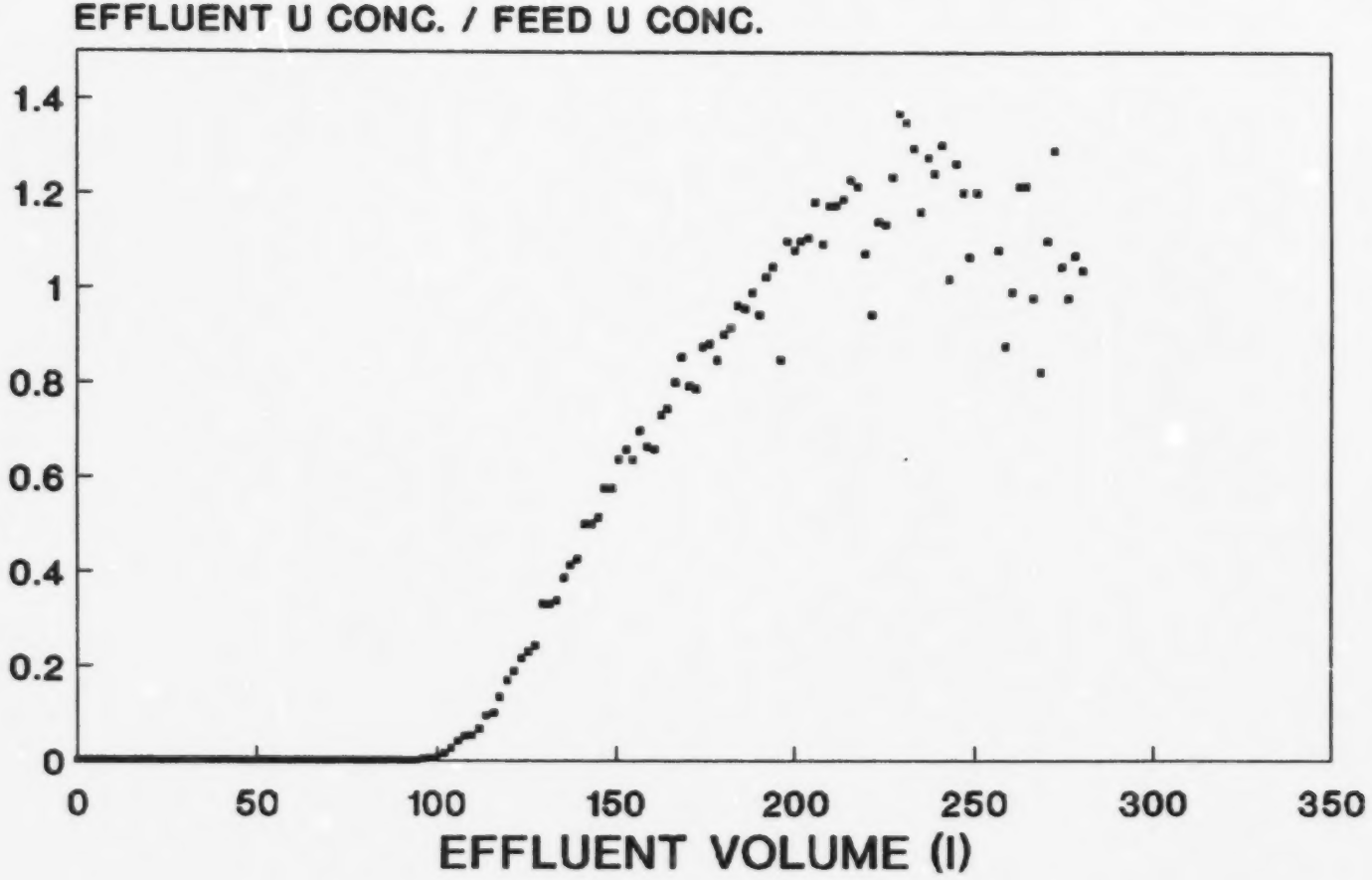
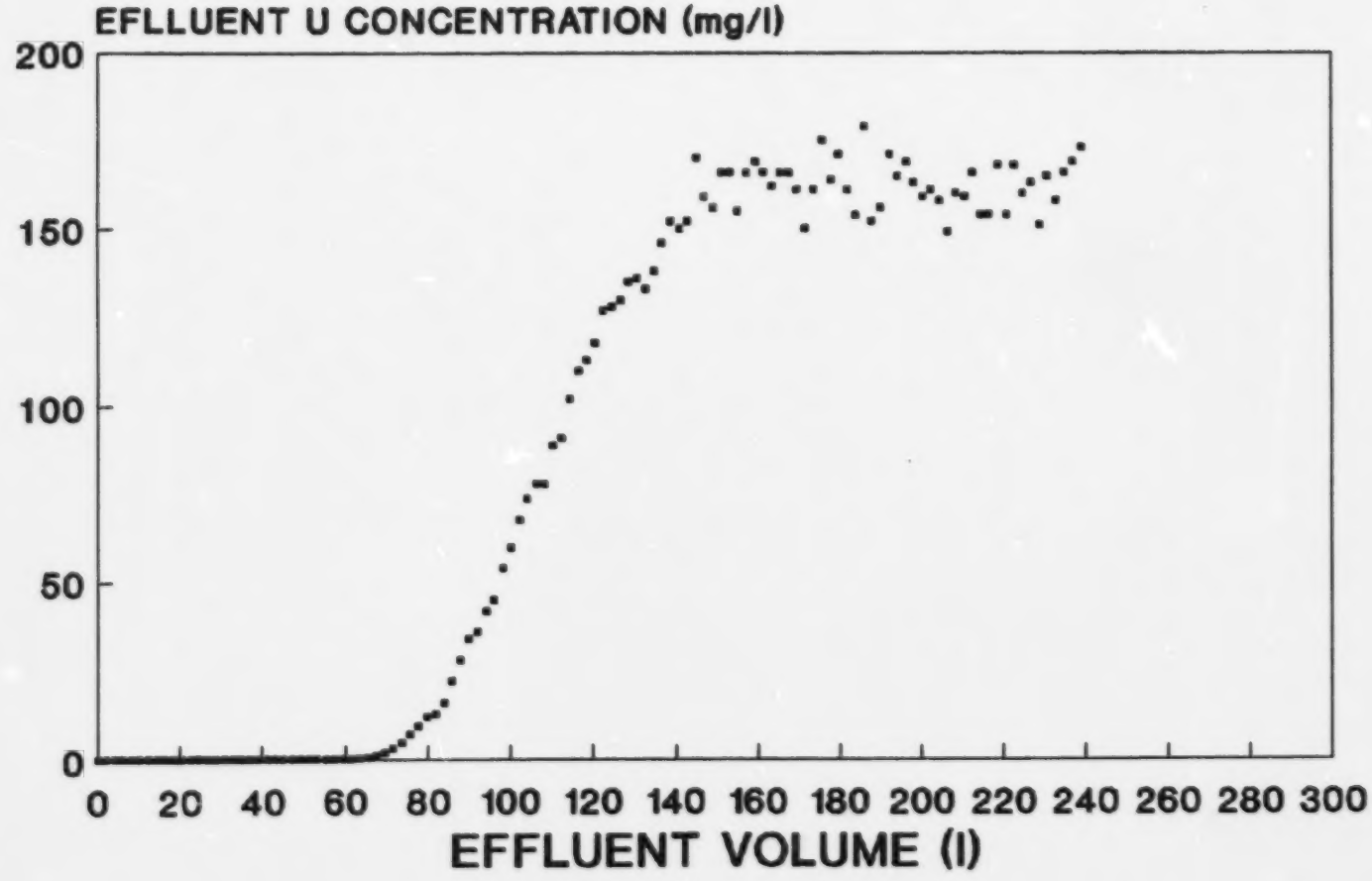
(Cycle 3)



LOADING BREAKTHROUGH CURVE
(Cycle 4)



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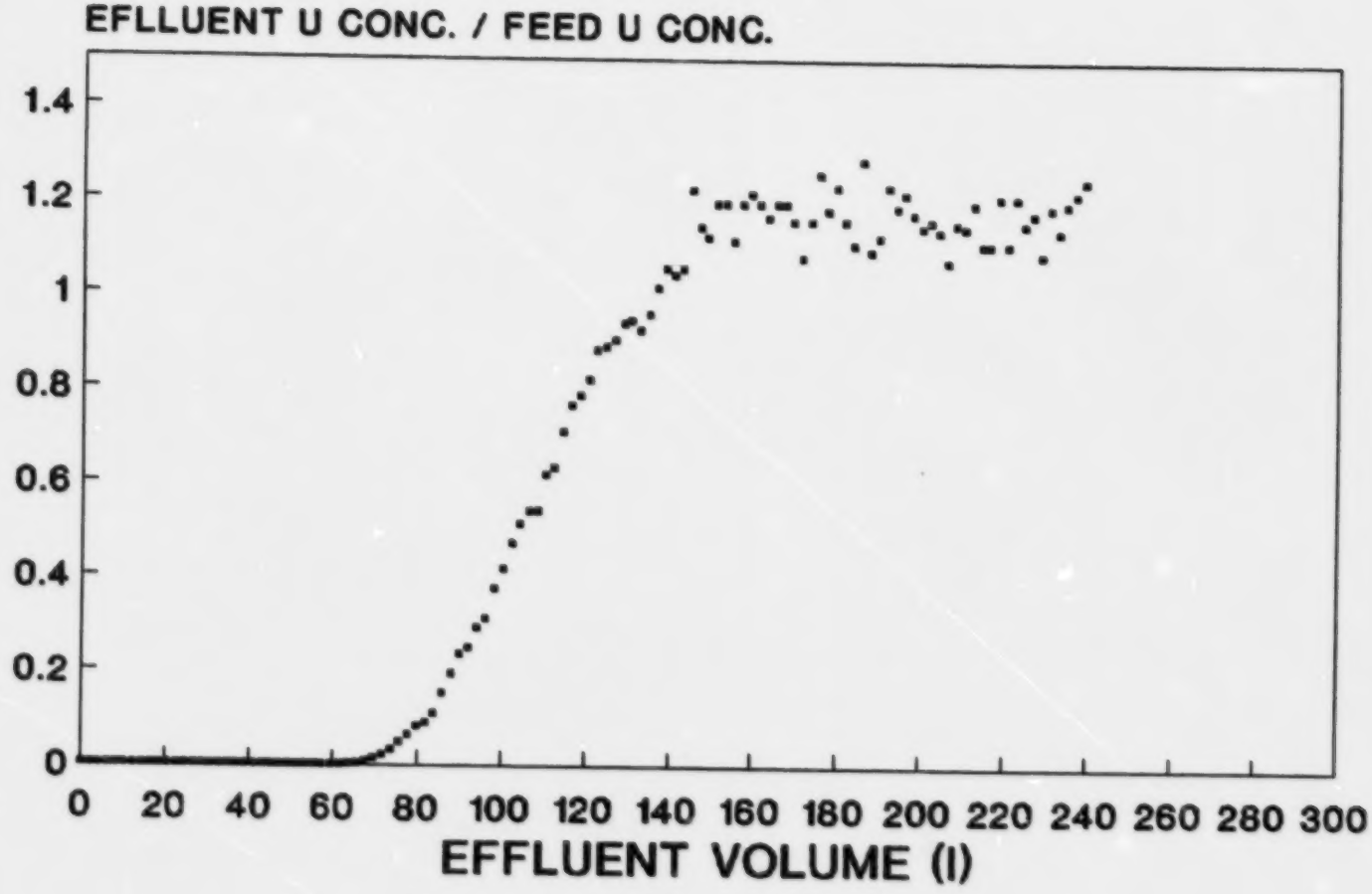
(Cycle 4)



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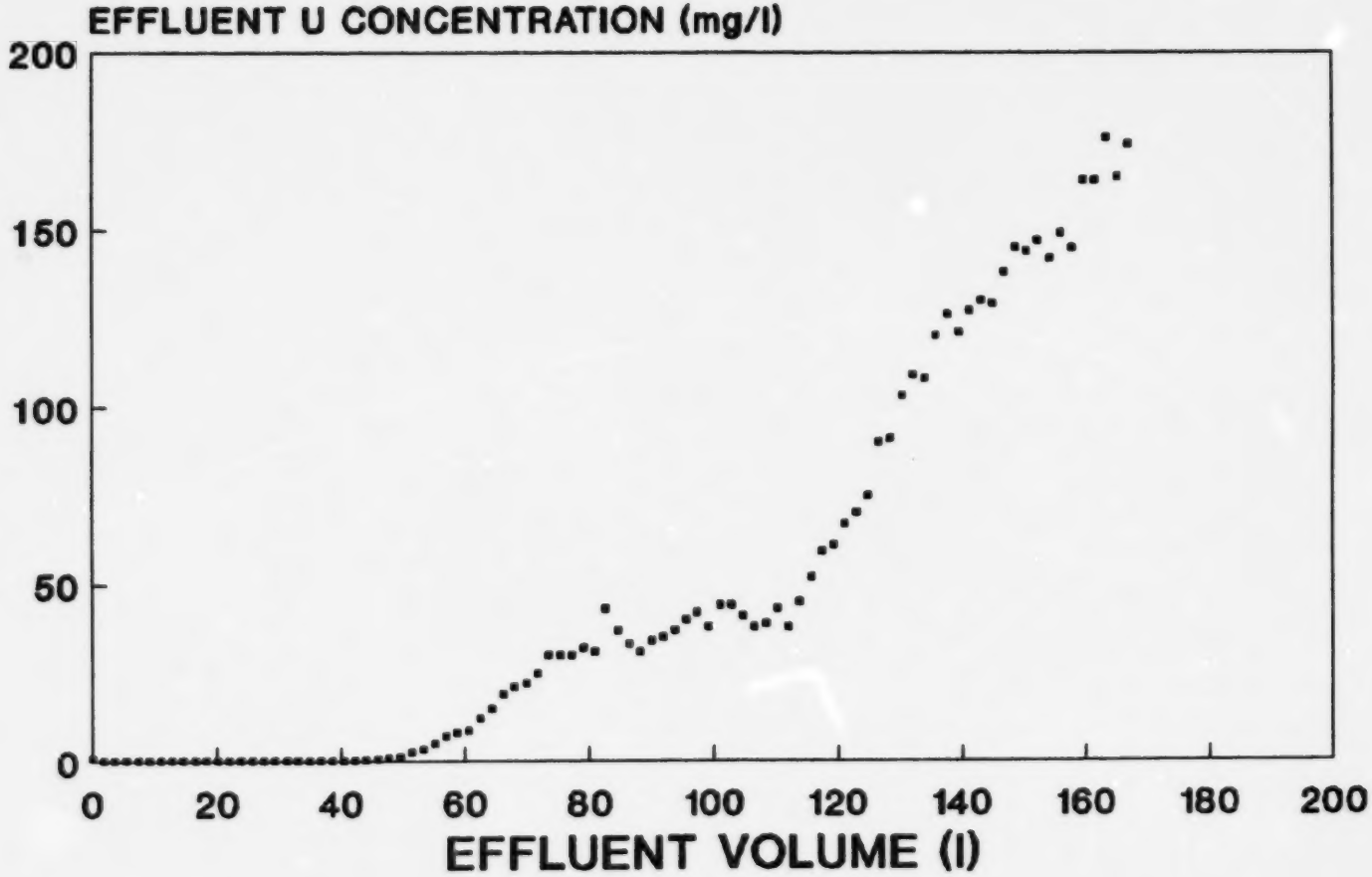
(Cycle 5)



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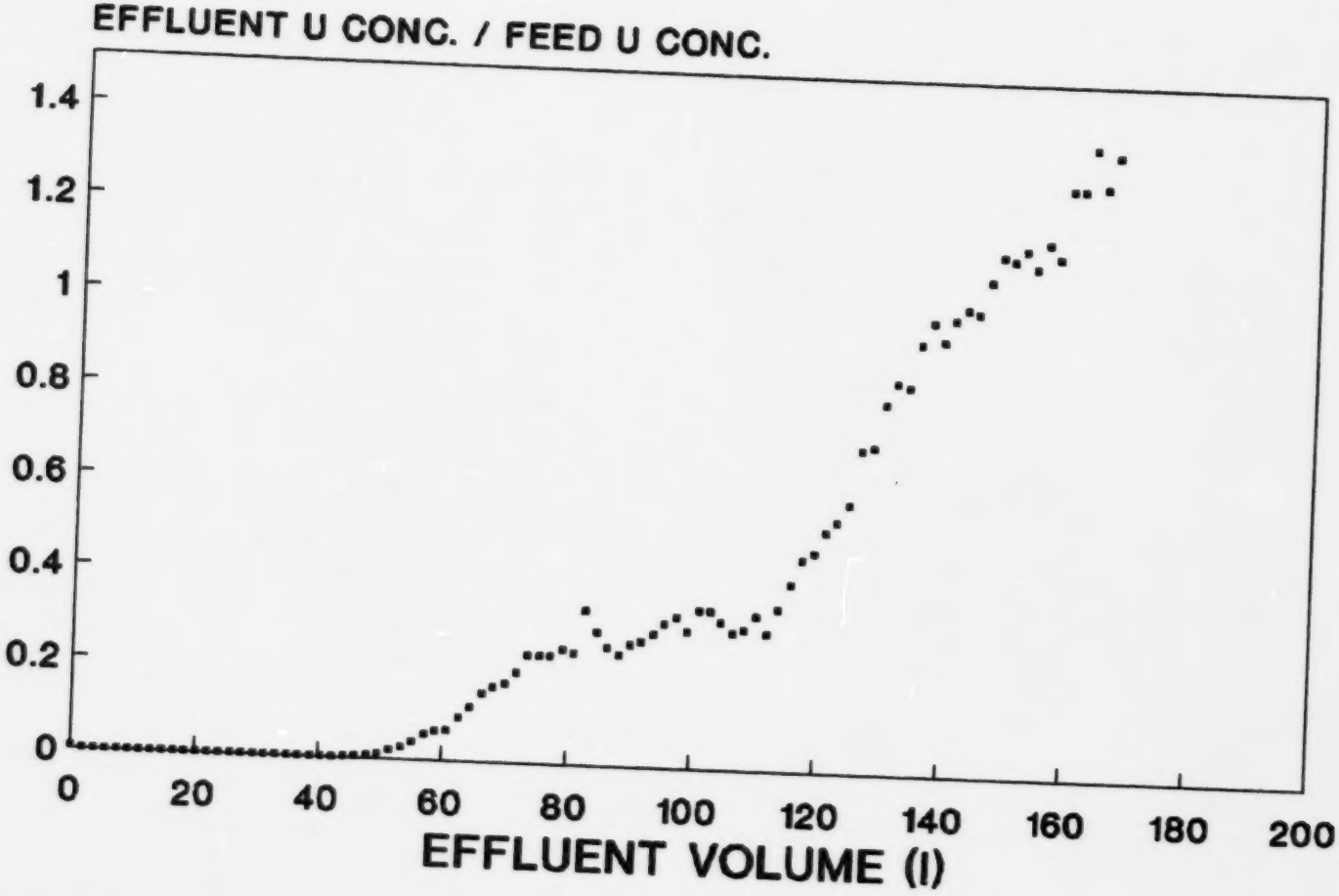

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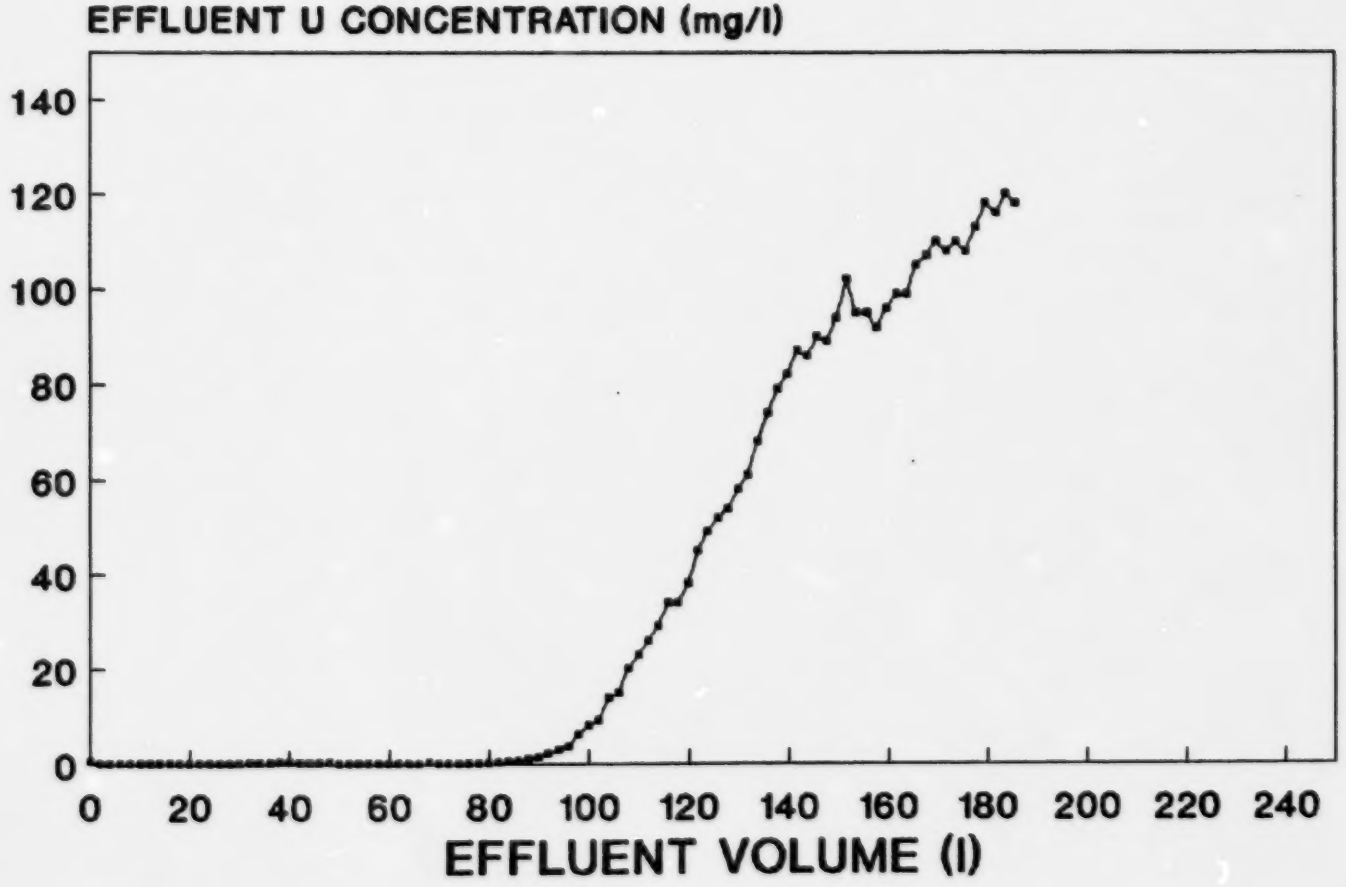

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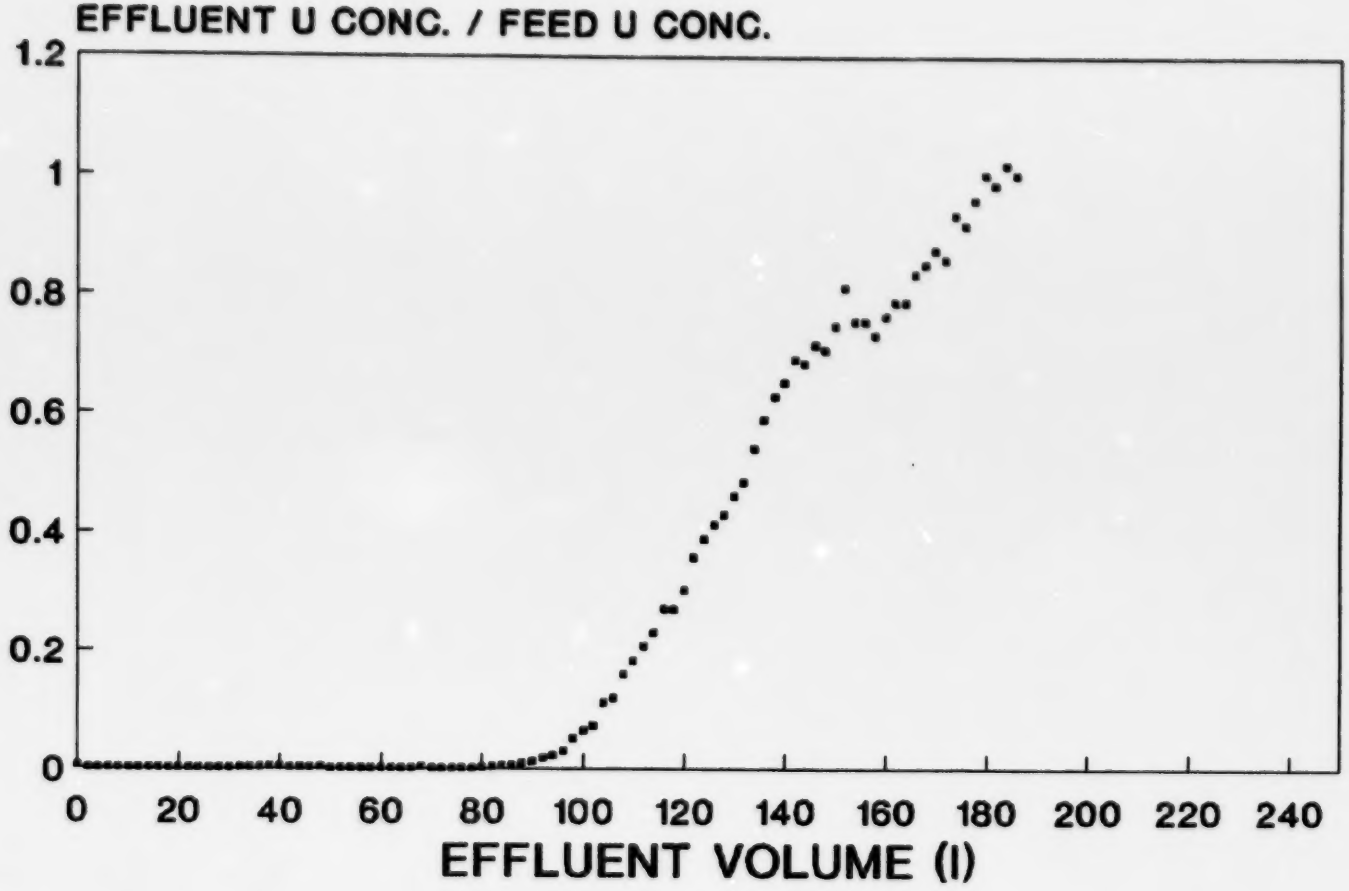
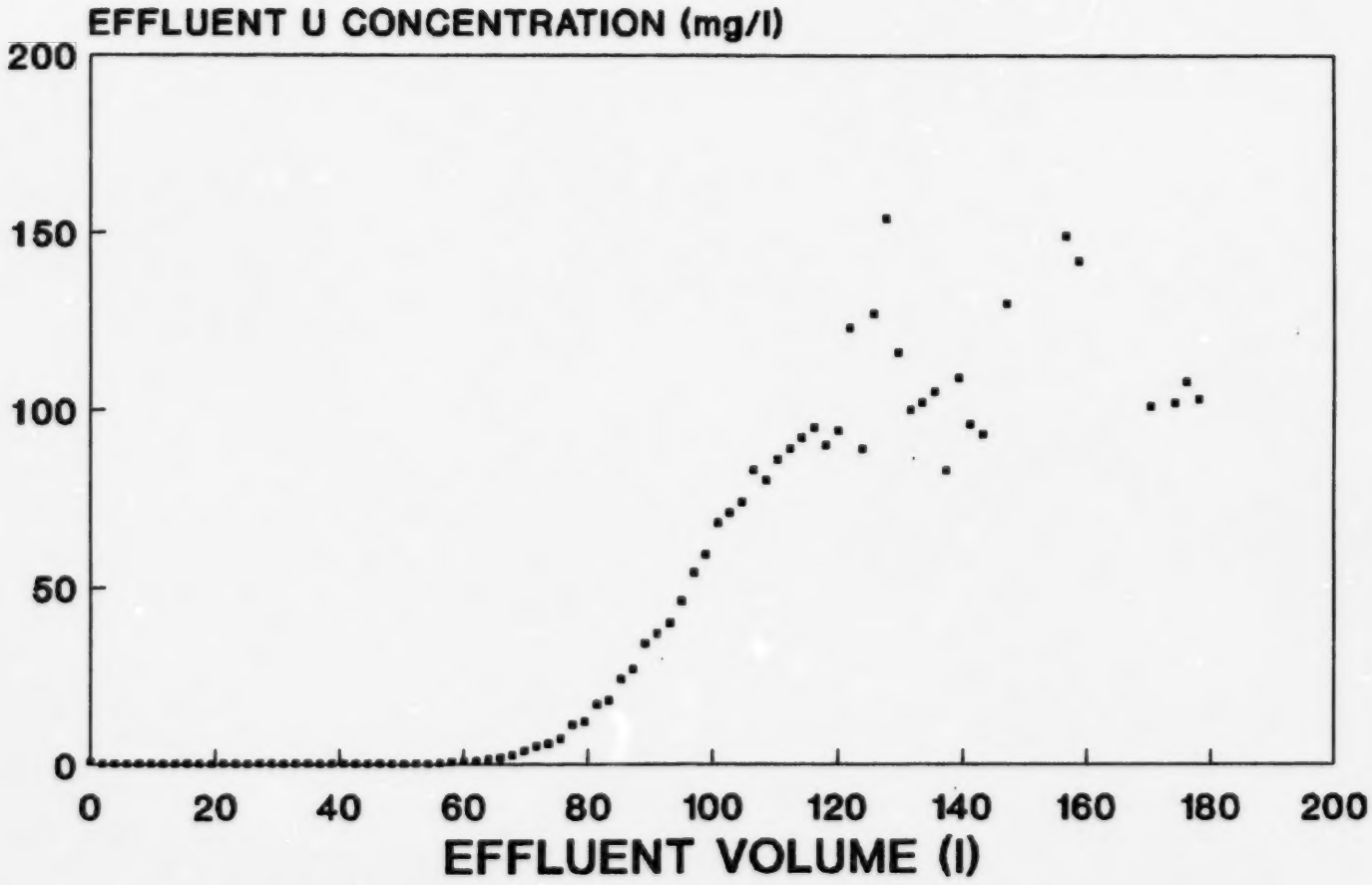


BREAKTHROUGH LOADING CURVE
(Cycle 7)



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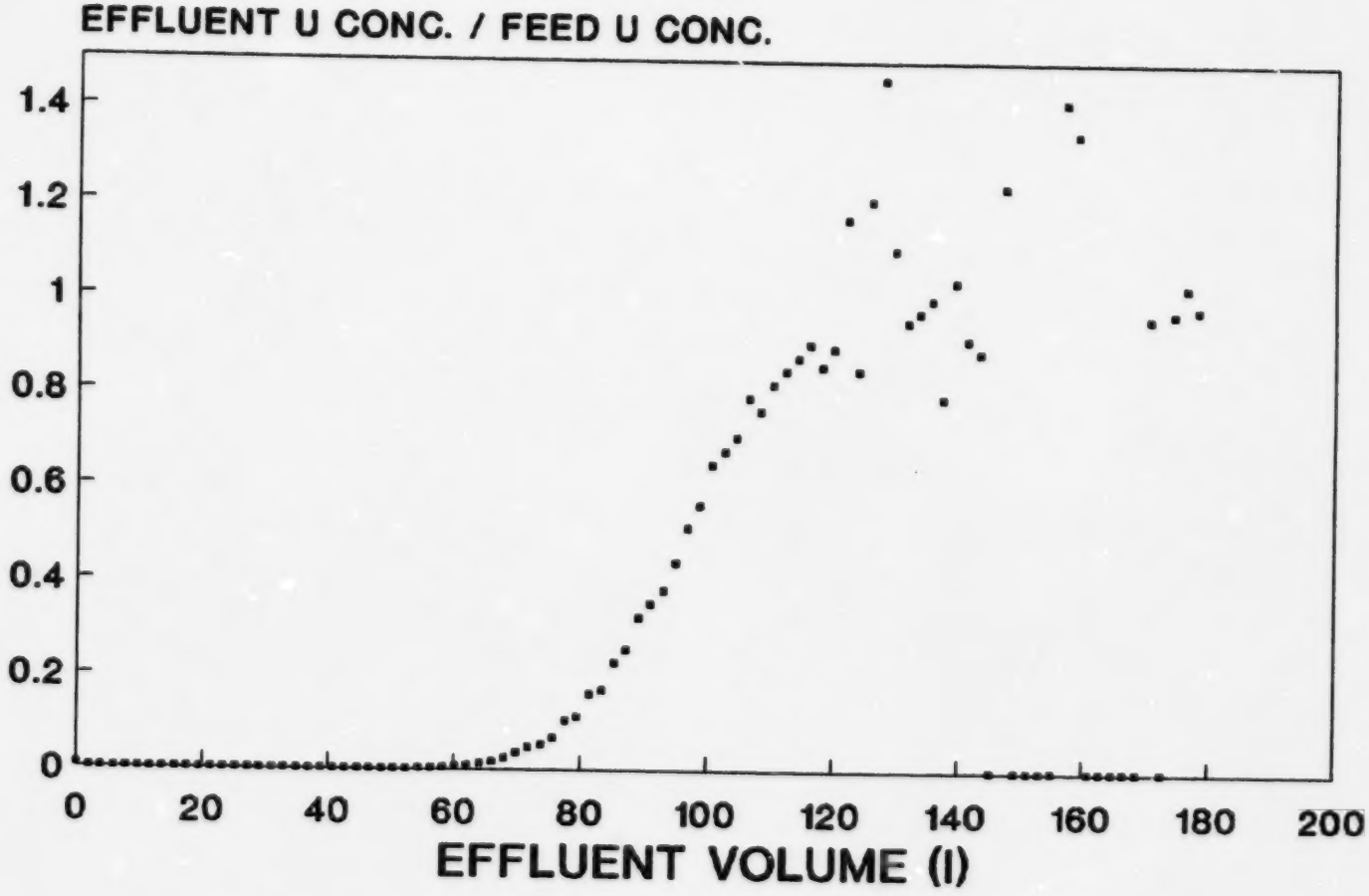

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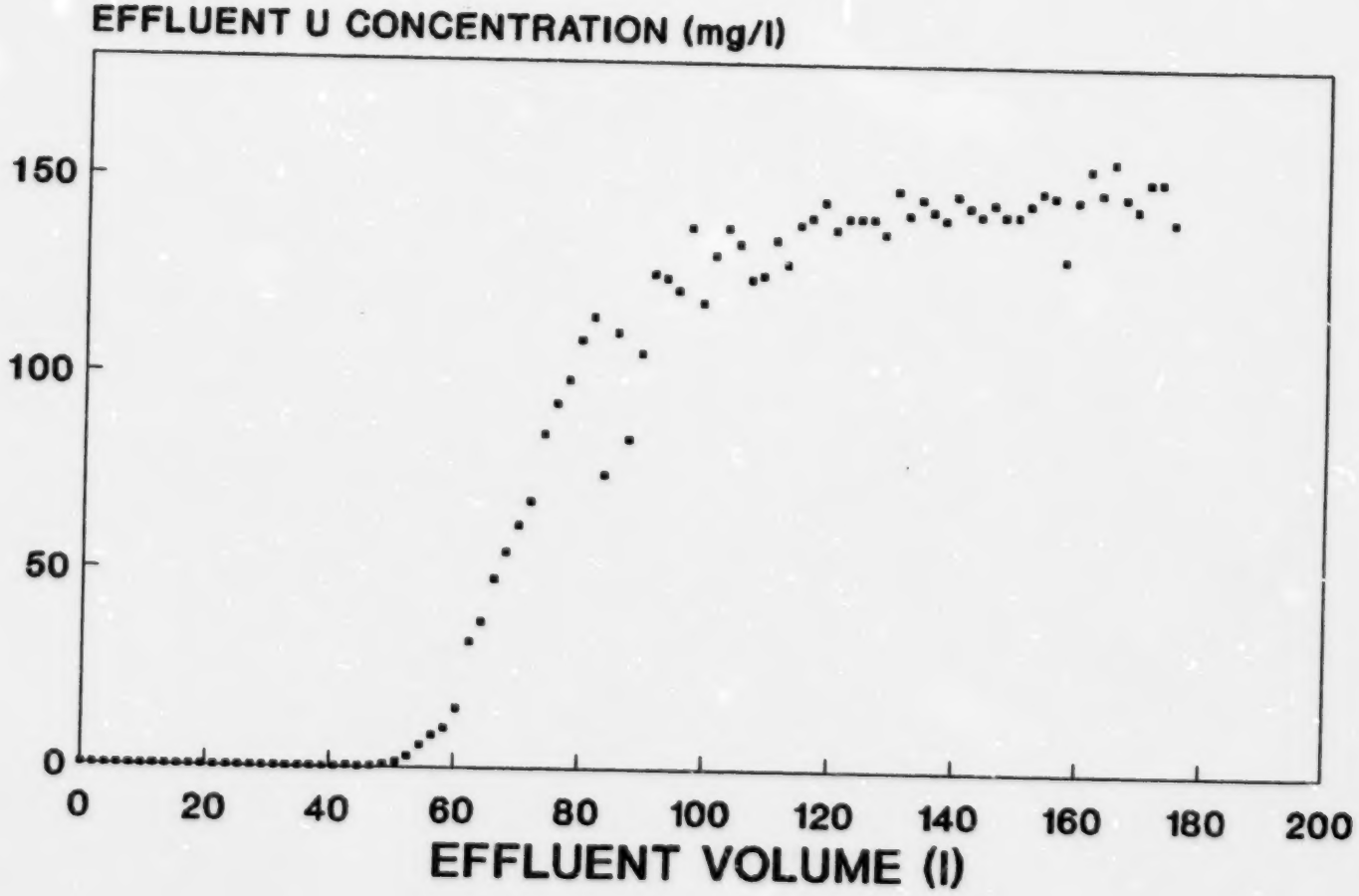

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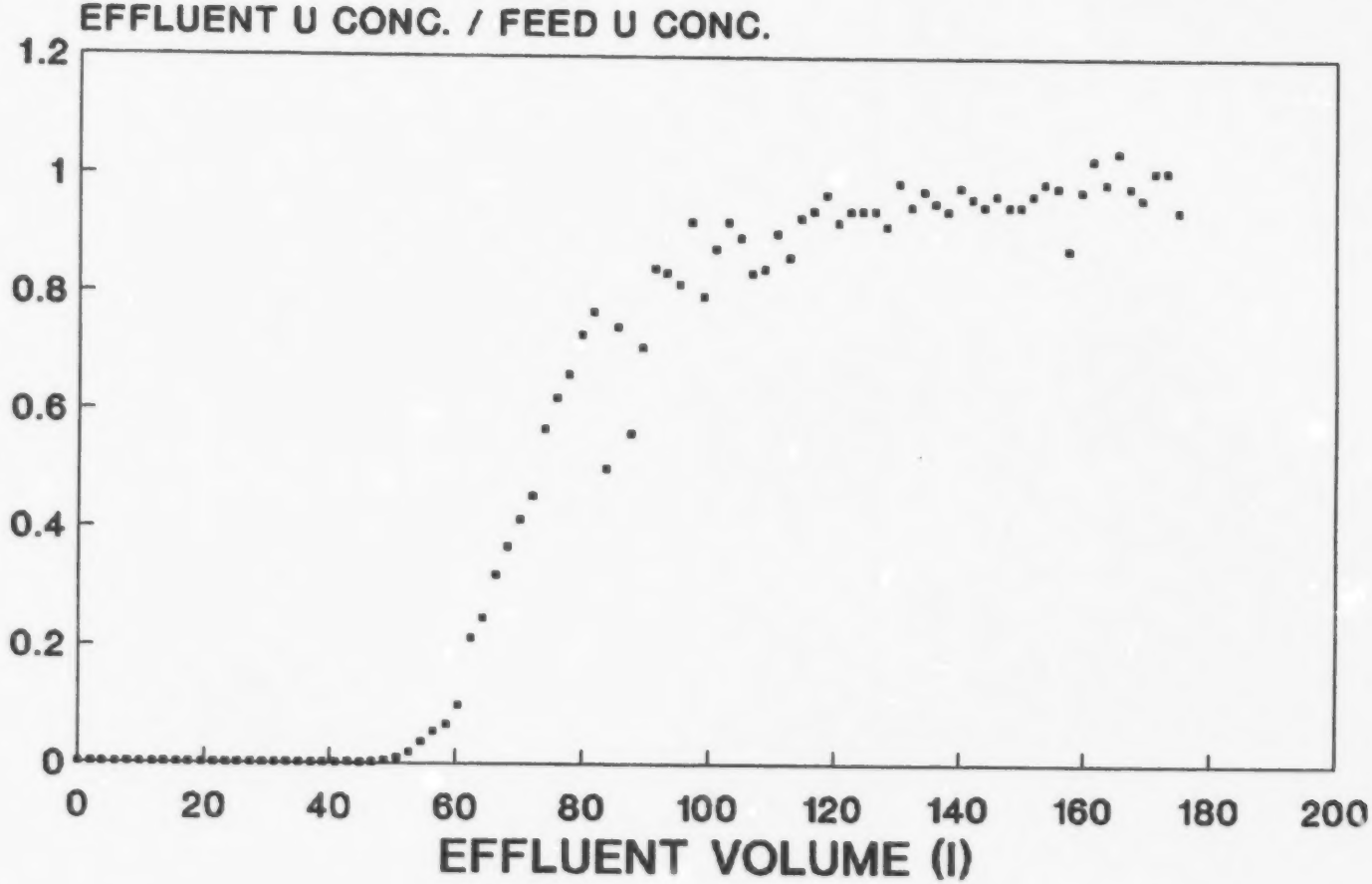

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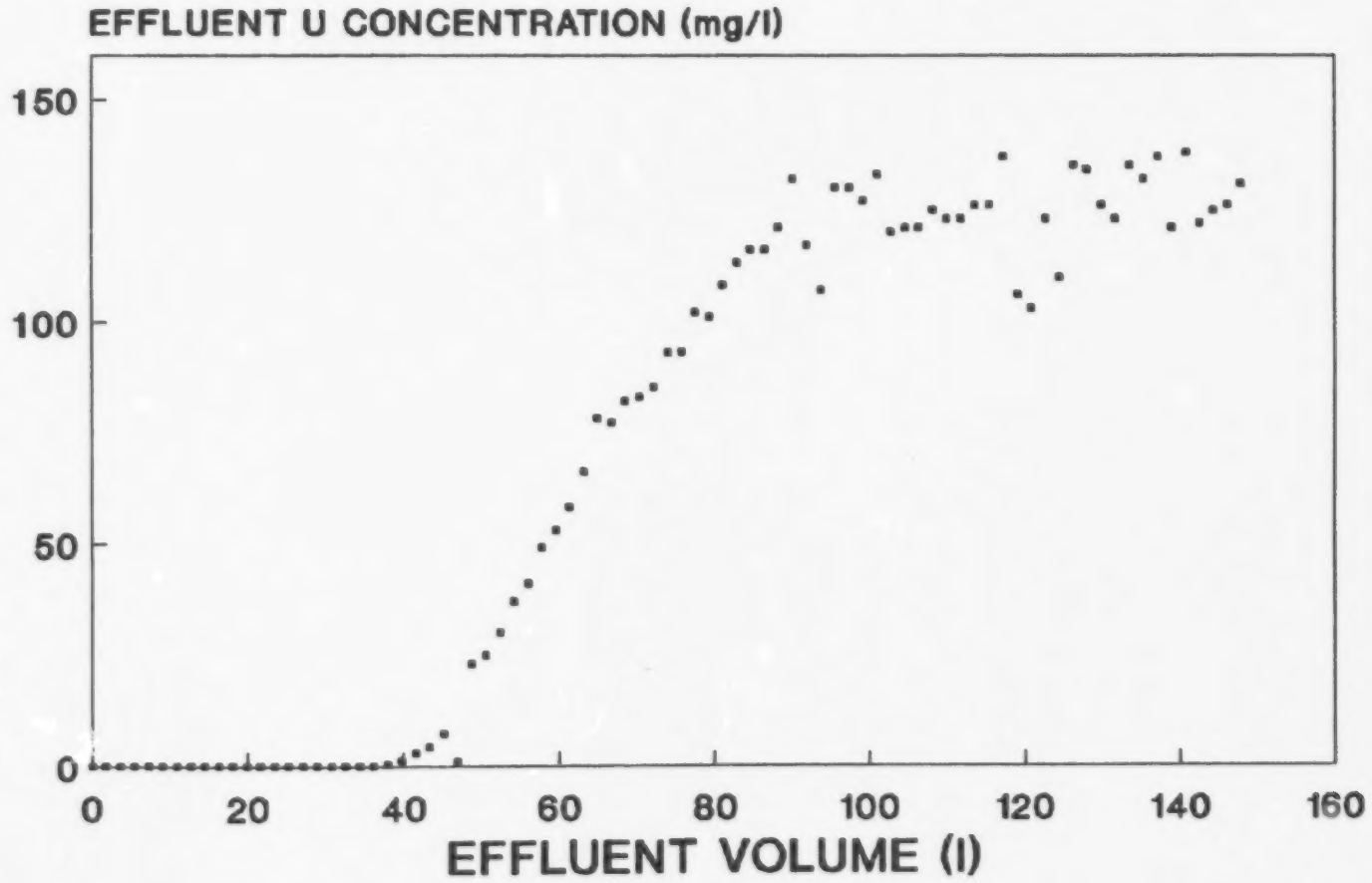

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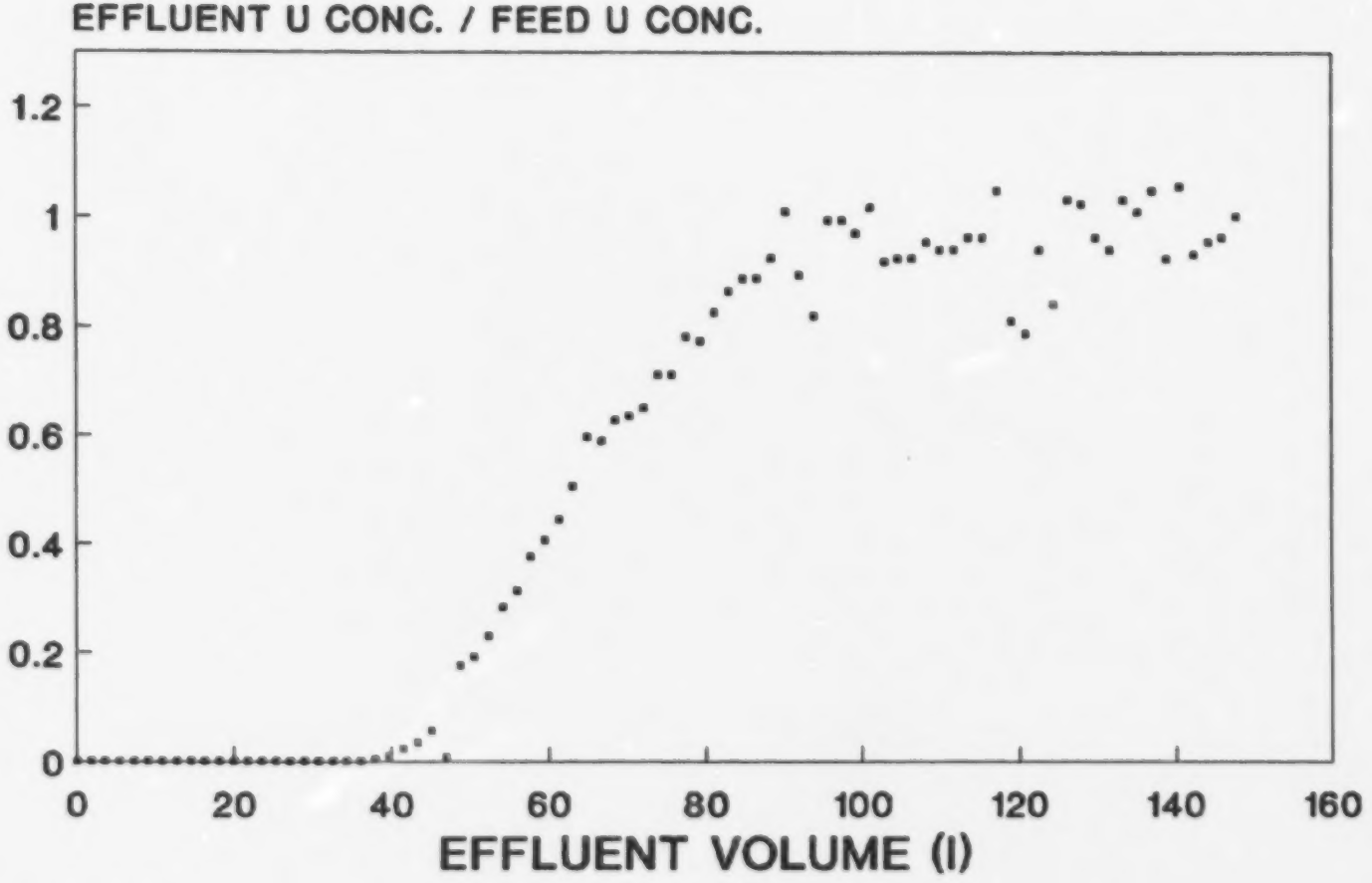

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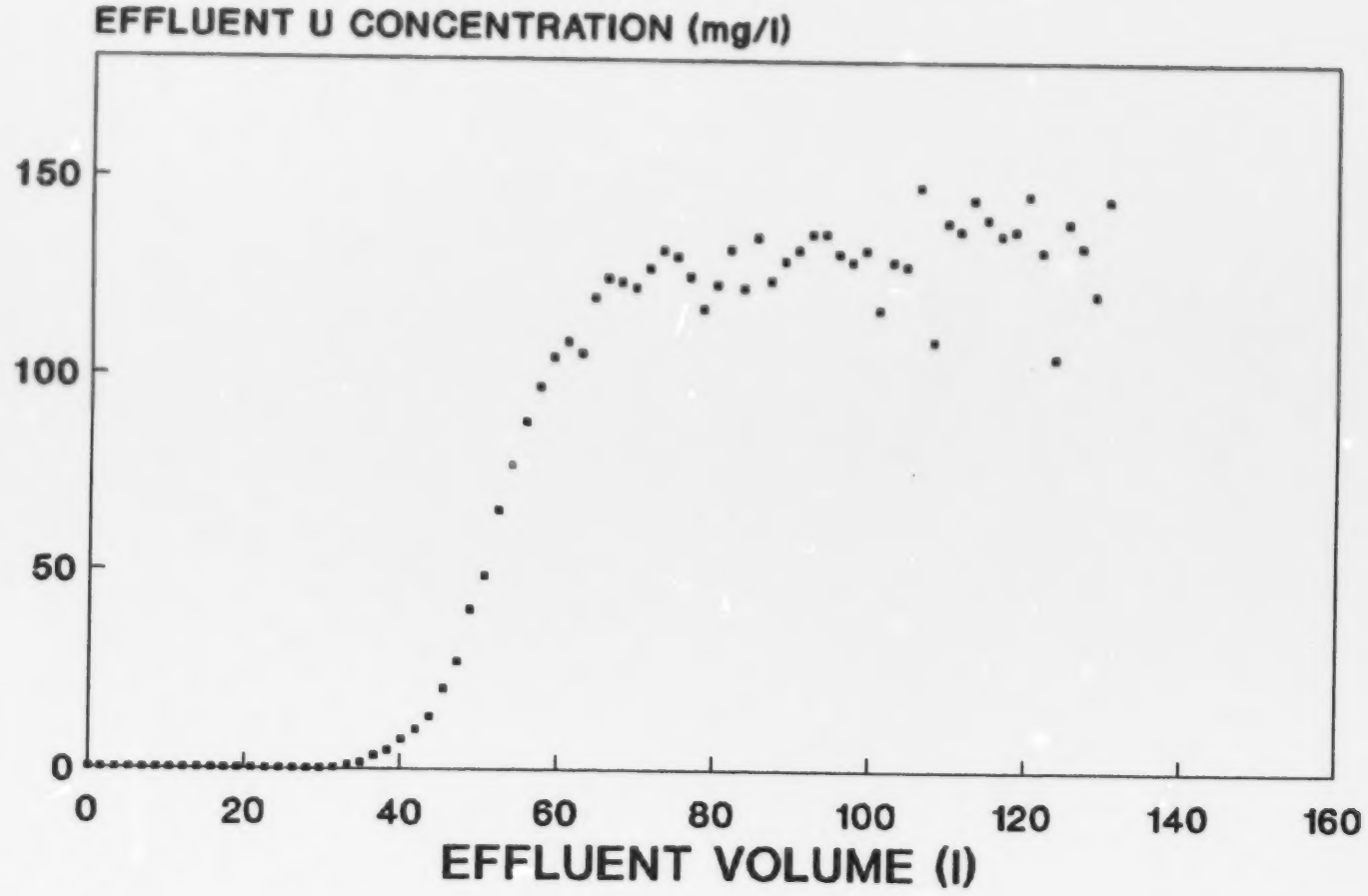
(Cycle 10)



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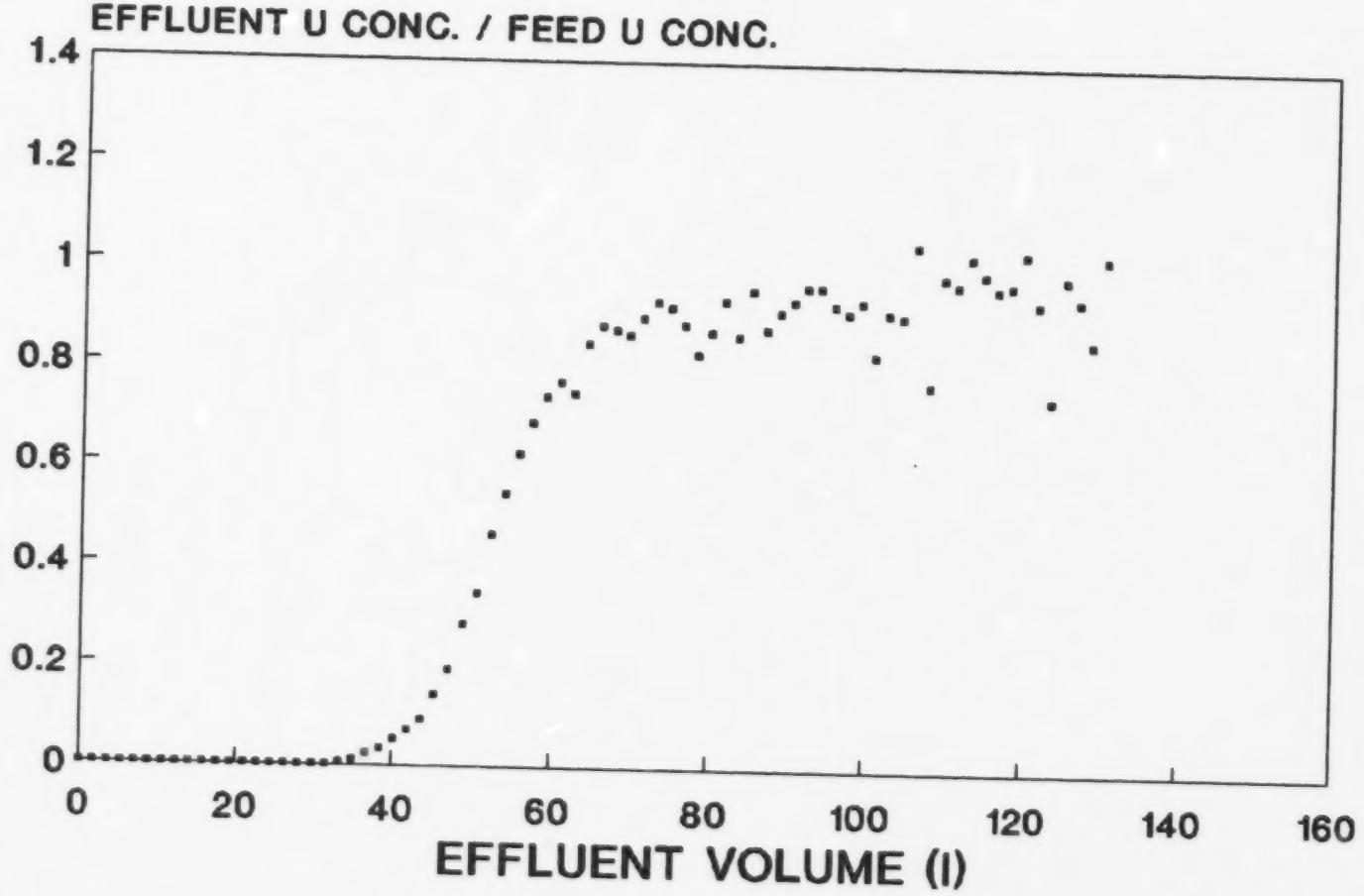

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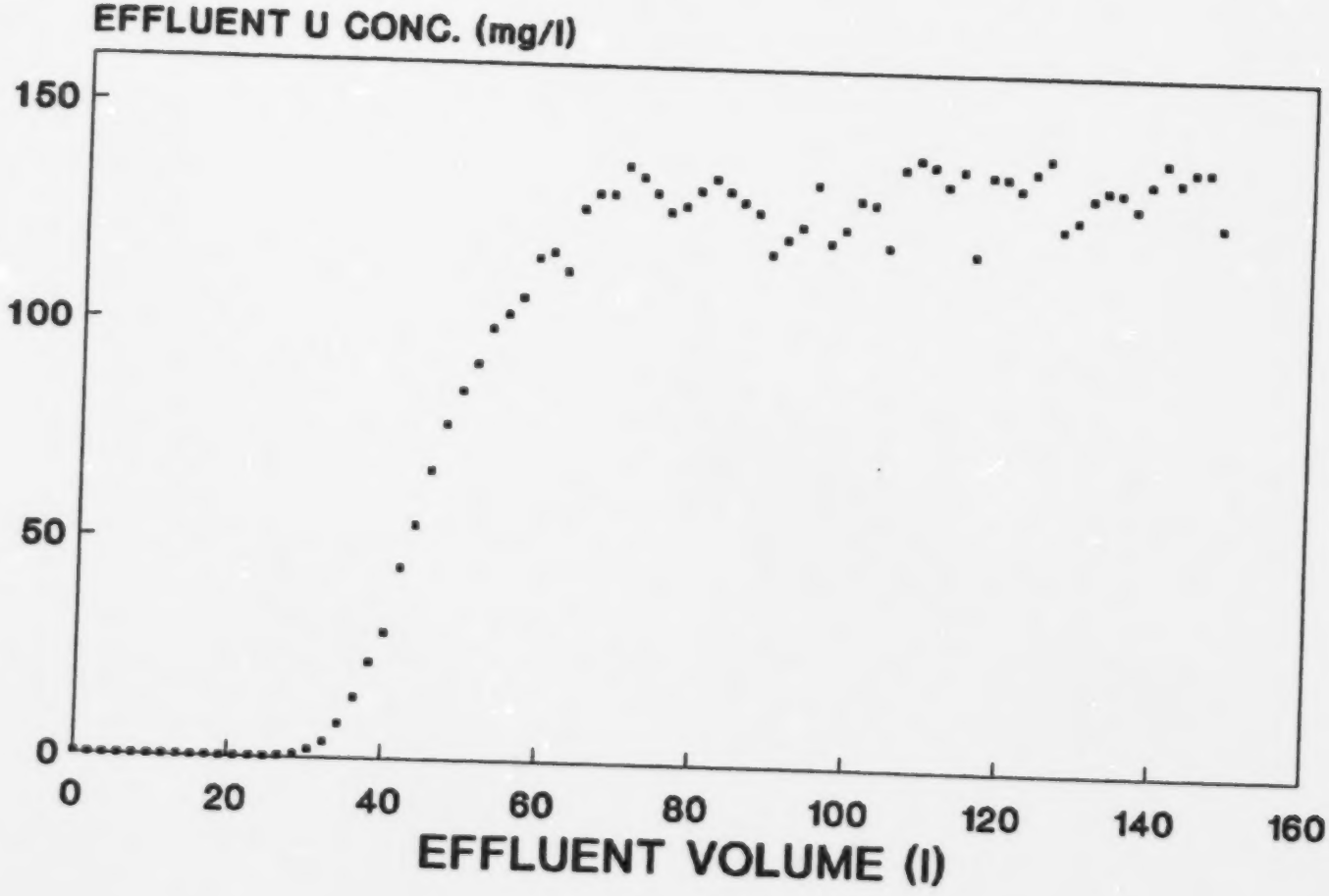

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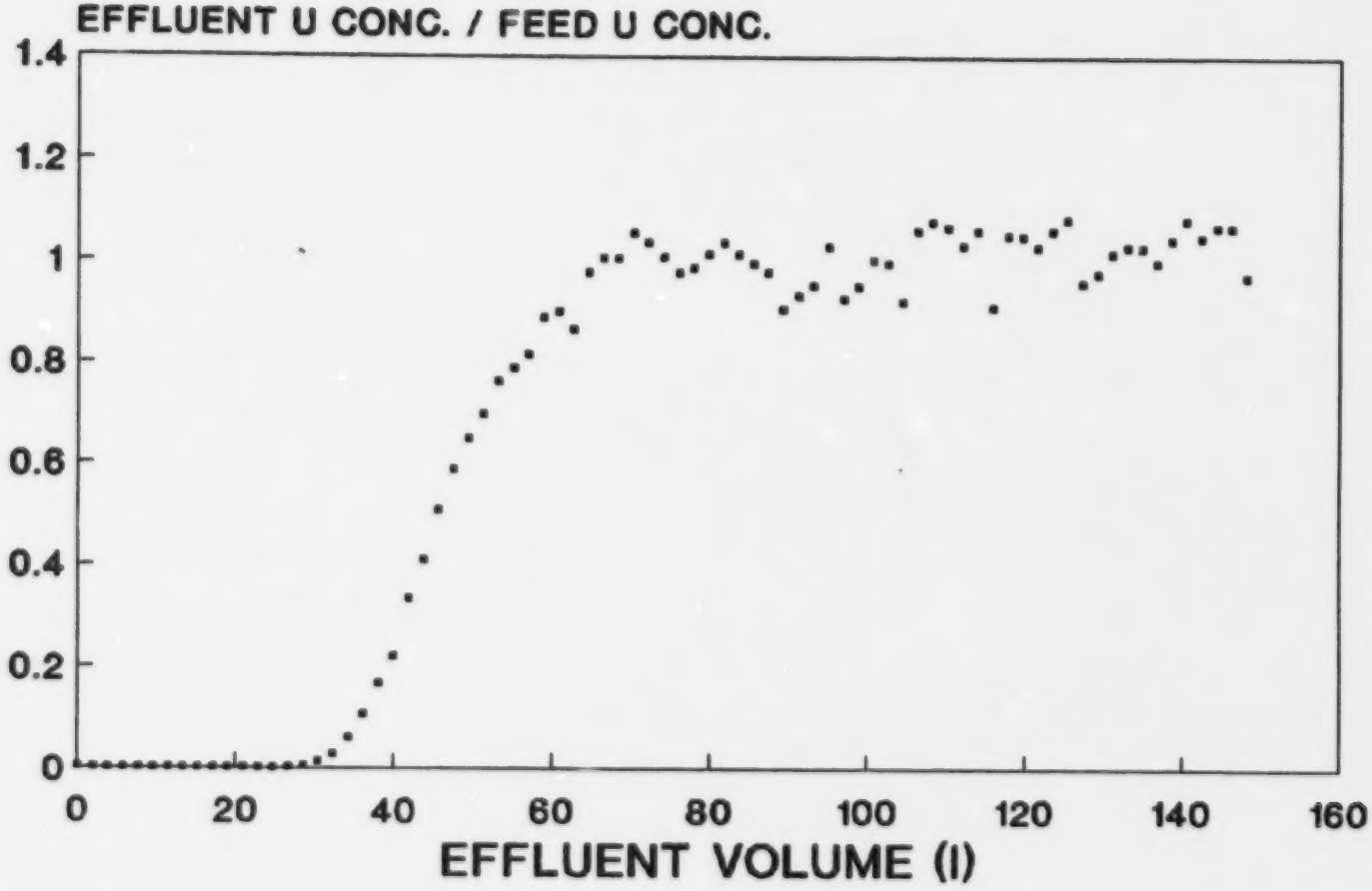
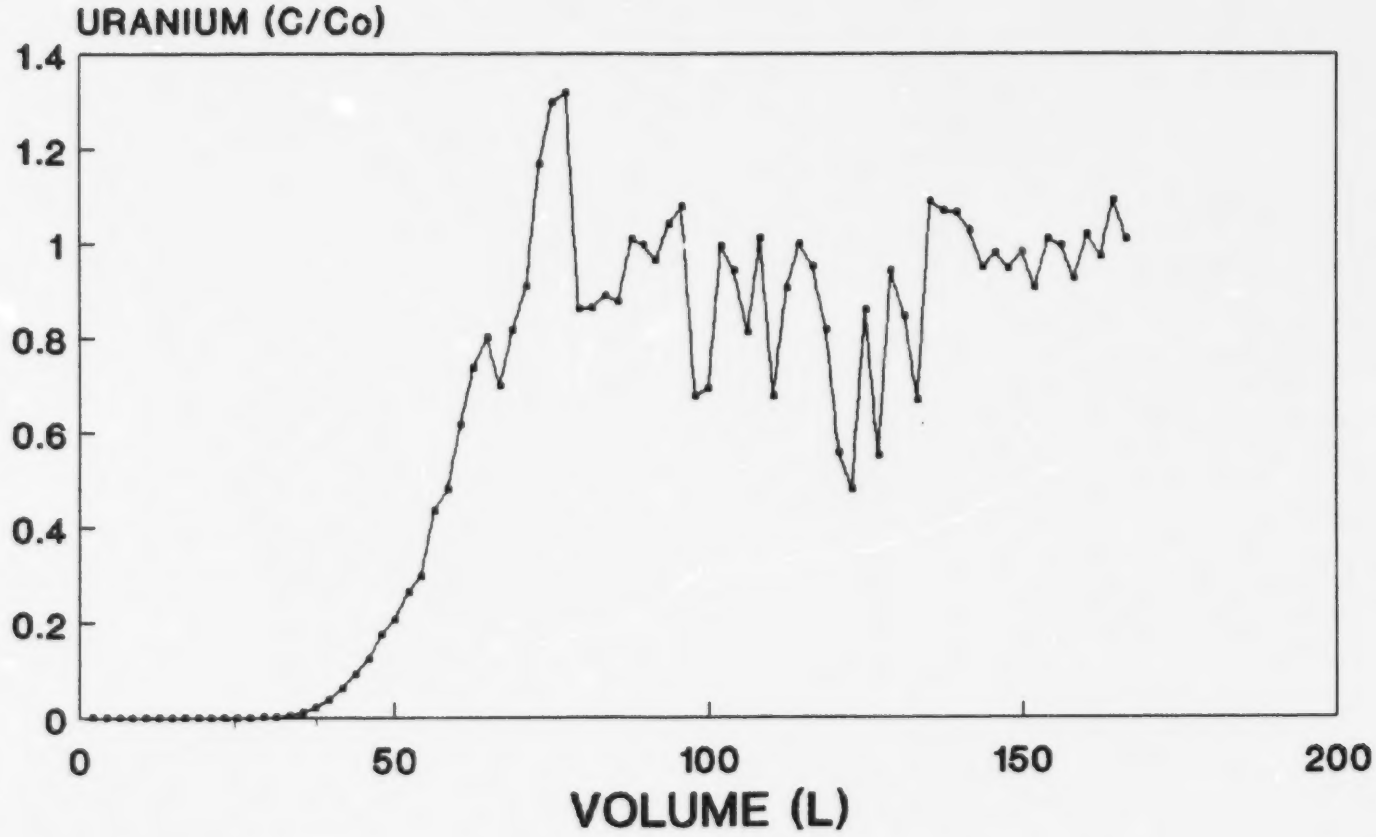
(Cycle 11)



BREAKTHROUGH CYCLE 12
LOADING



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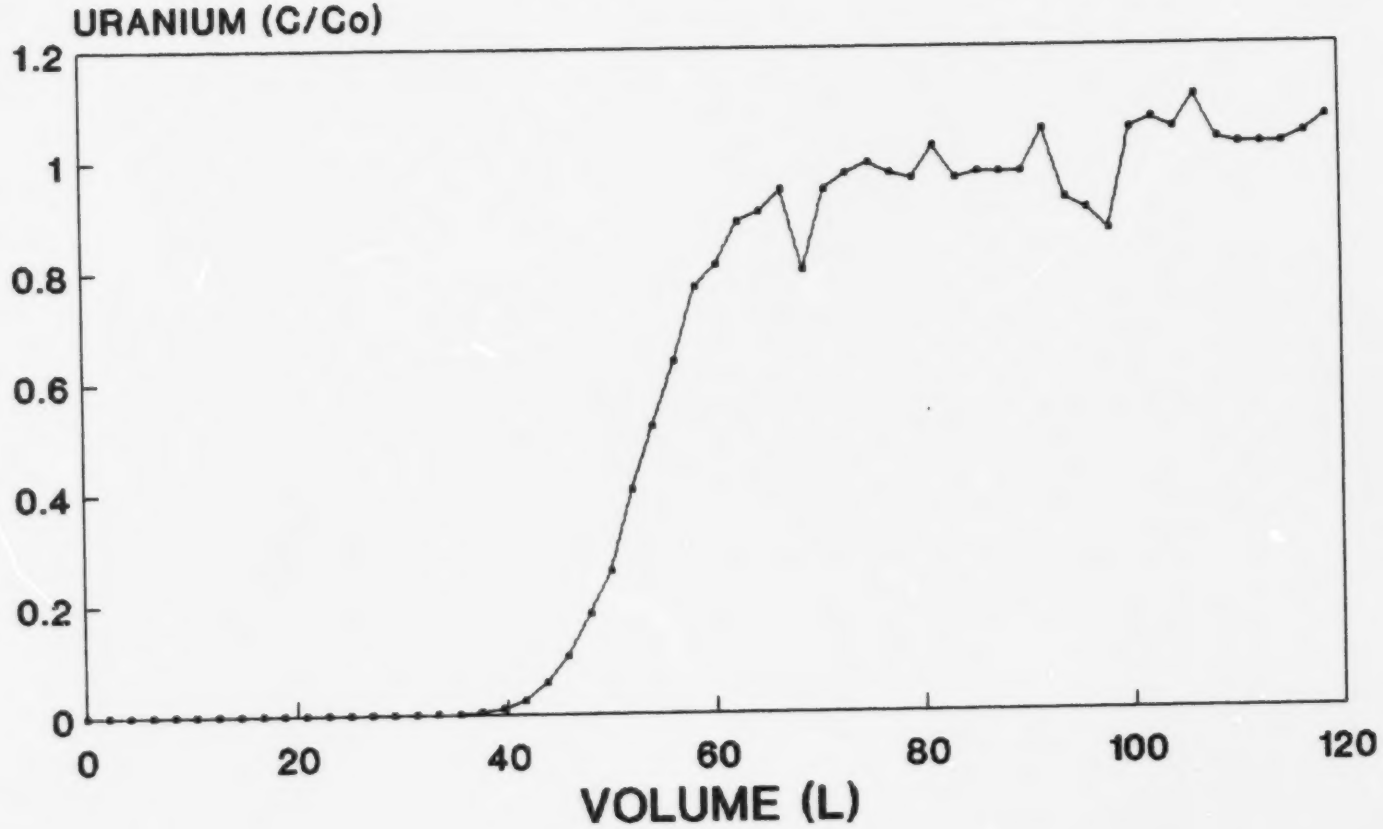
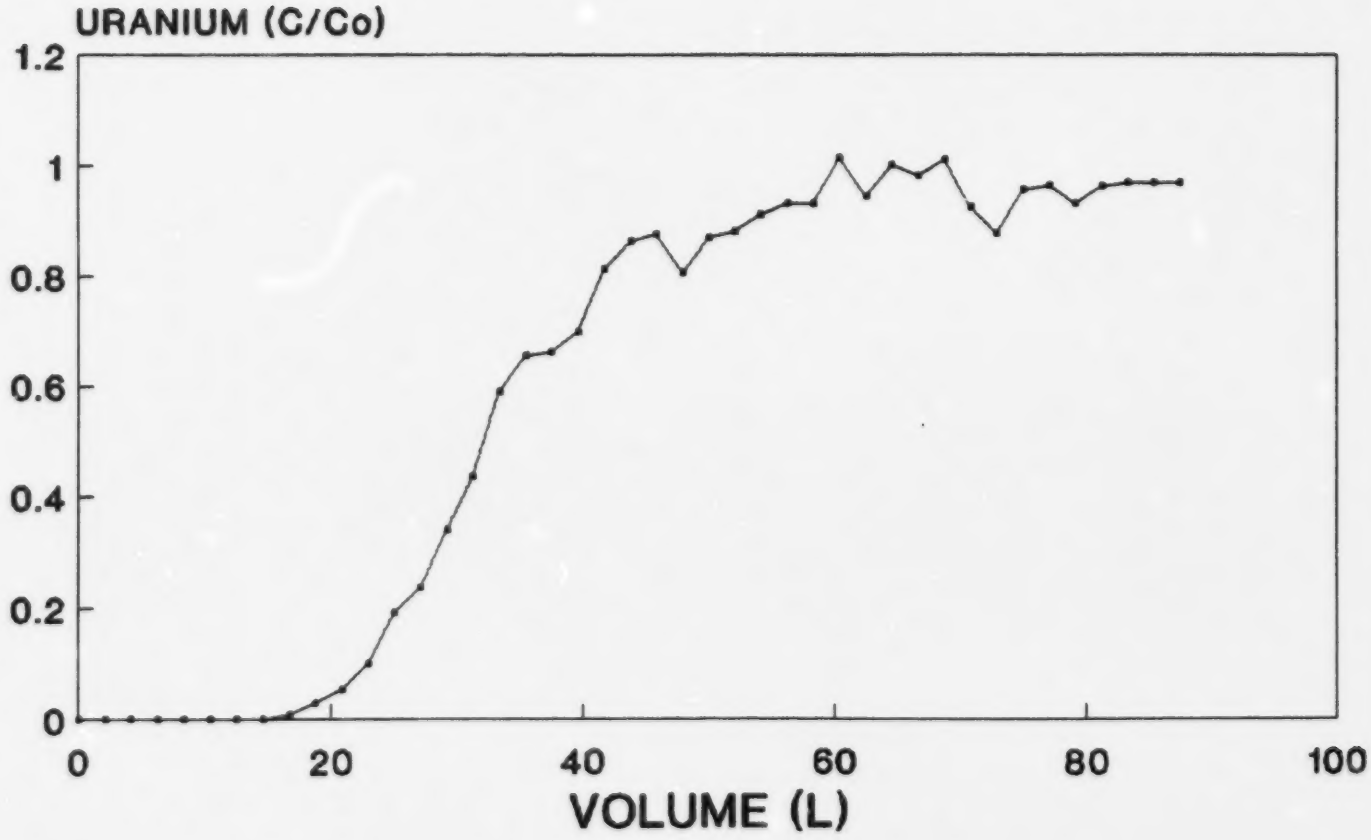
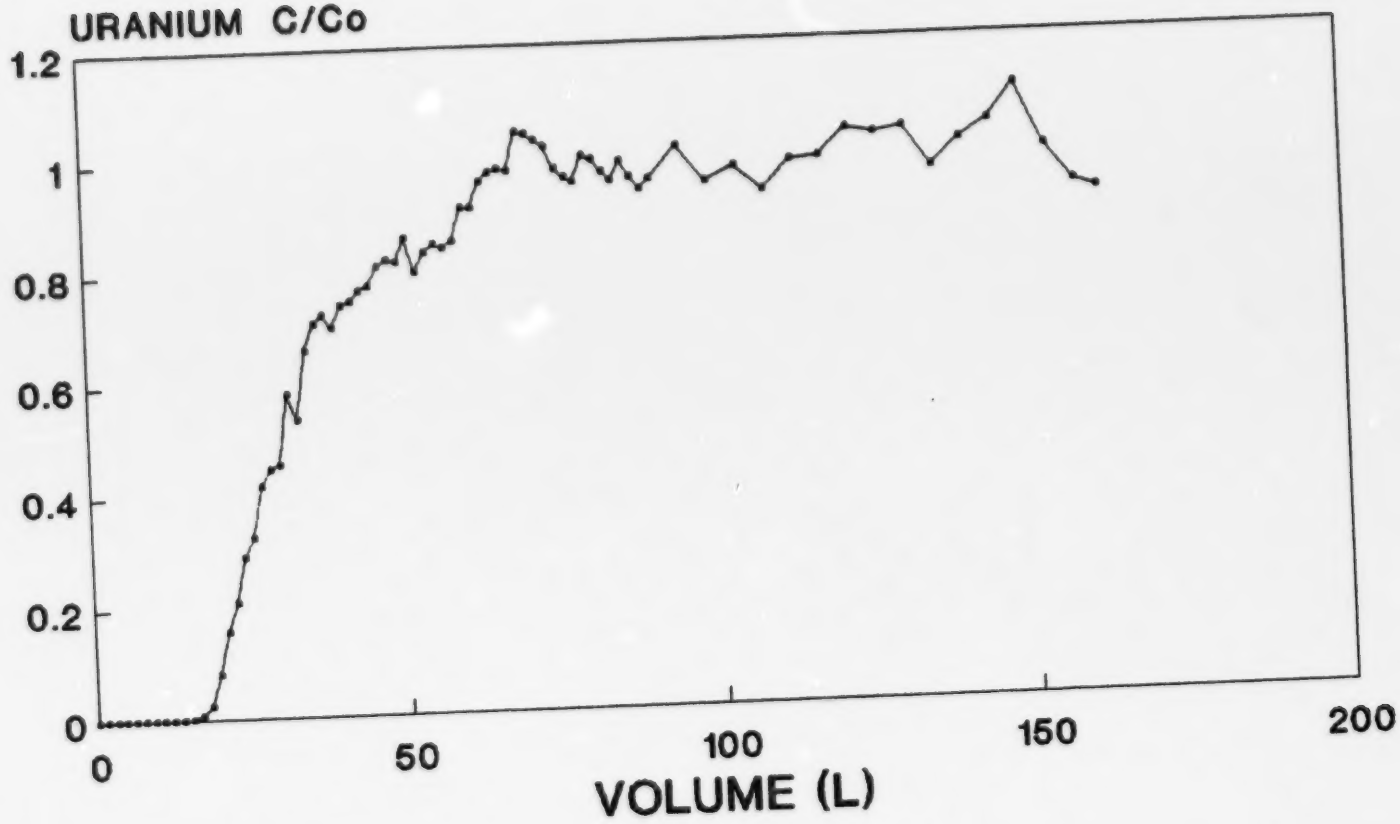


LOADING
CYCLE 14

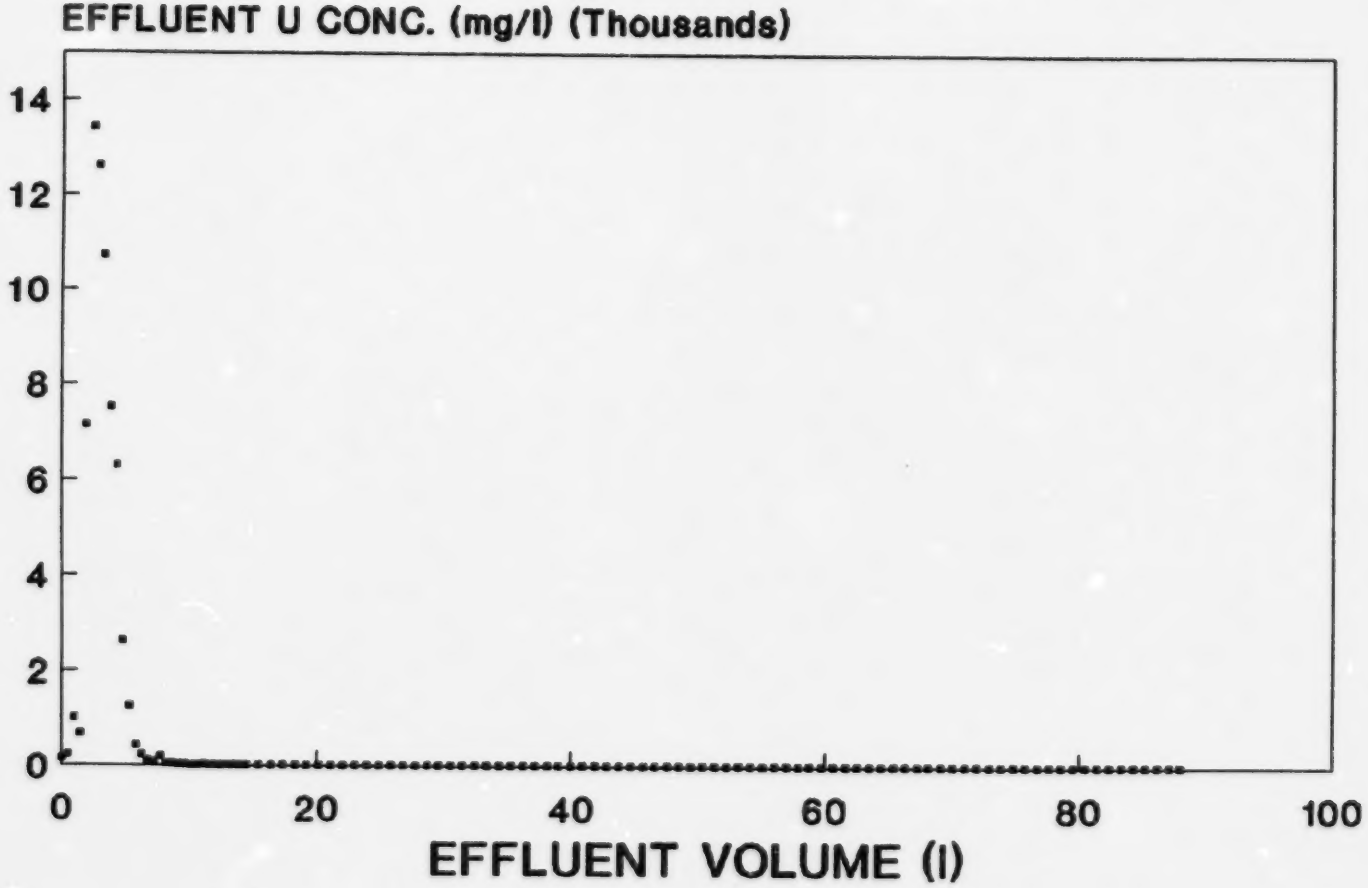


LOADING
CYCLE 15

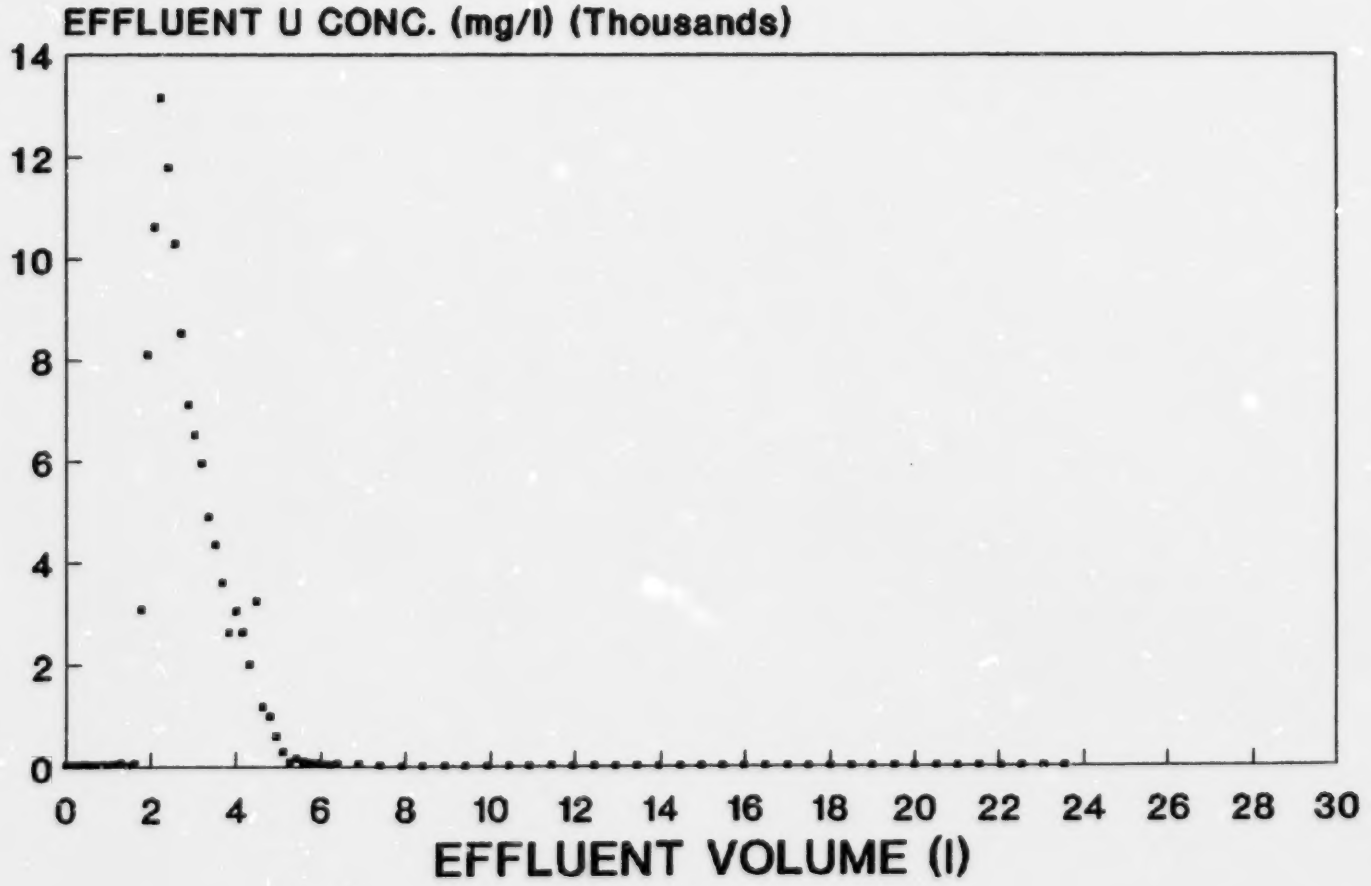


APPENDIX 2

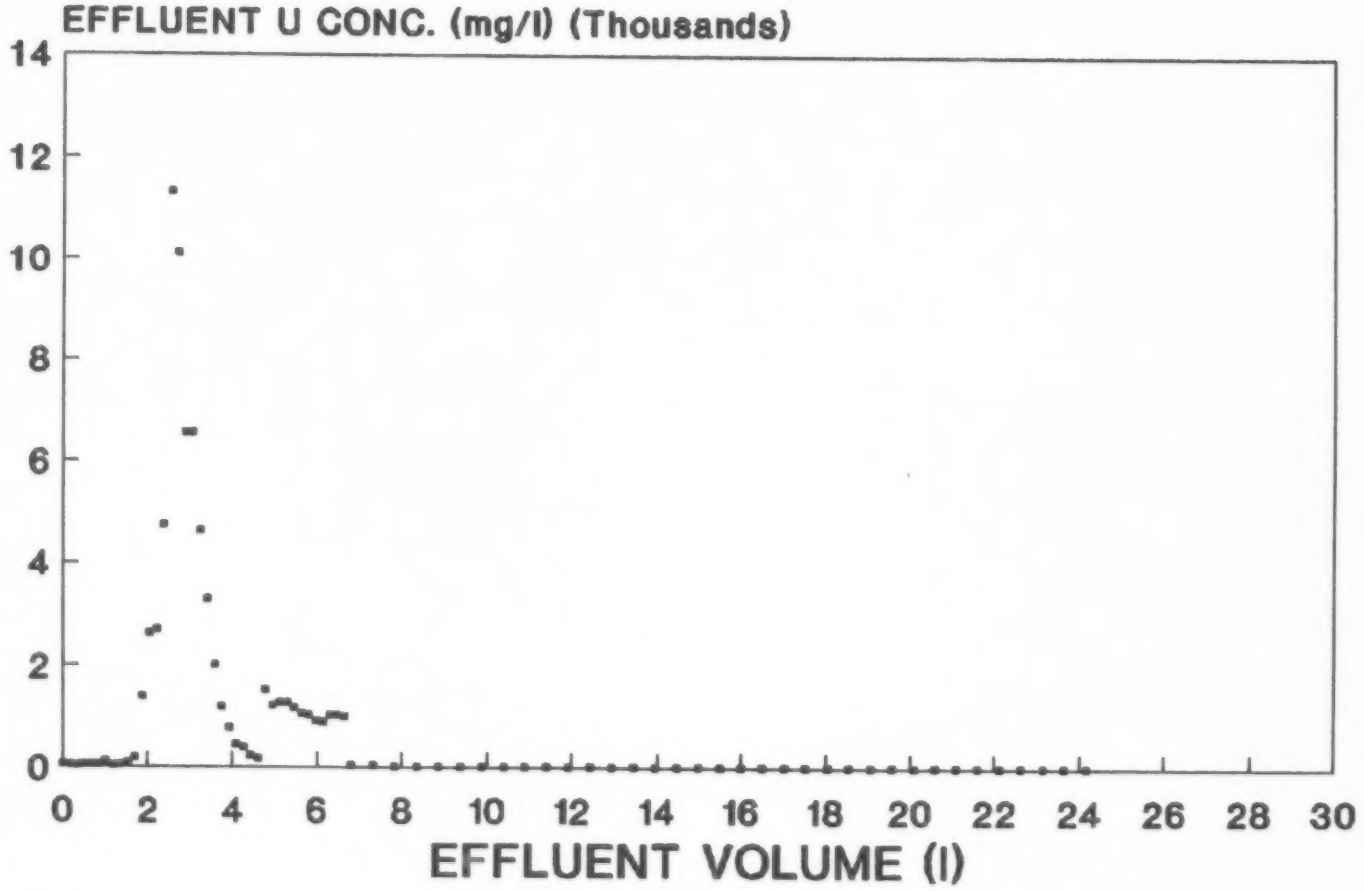
ELUTION BREAKTHROUGH CURVE
(Cycle 1)



ELUTION BREAKTHROUGH CURVE
(Cycle 2)



ELUTION BREAKTHROUGH CURVE
(Cycle 3)



ELUTION BREAKTHROUGH CURVE
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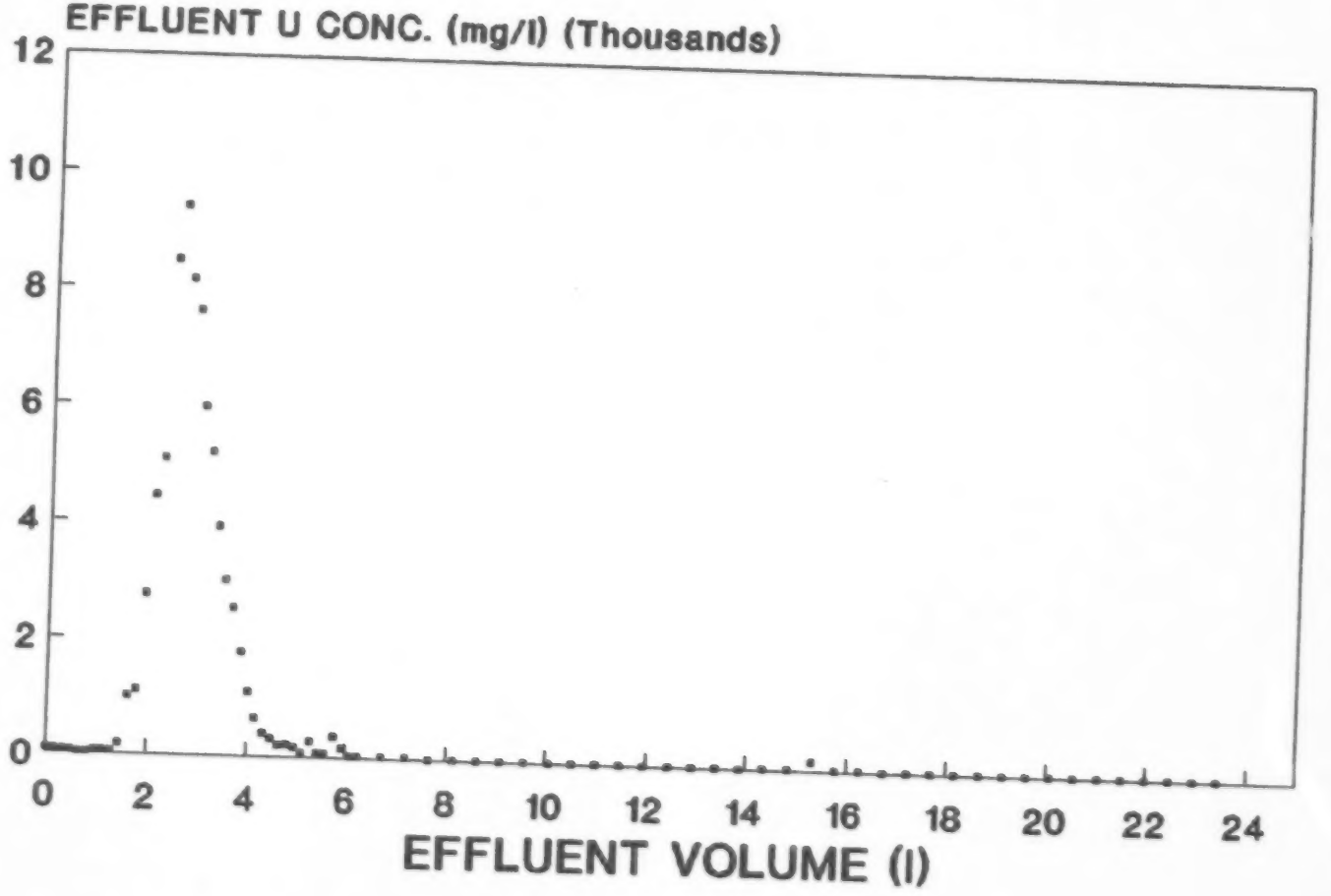

ELUTION BREAKTHROUGH CURVE
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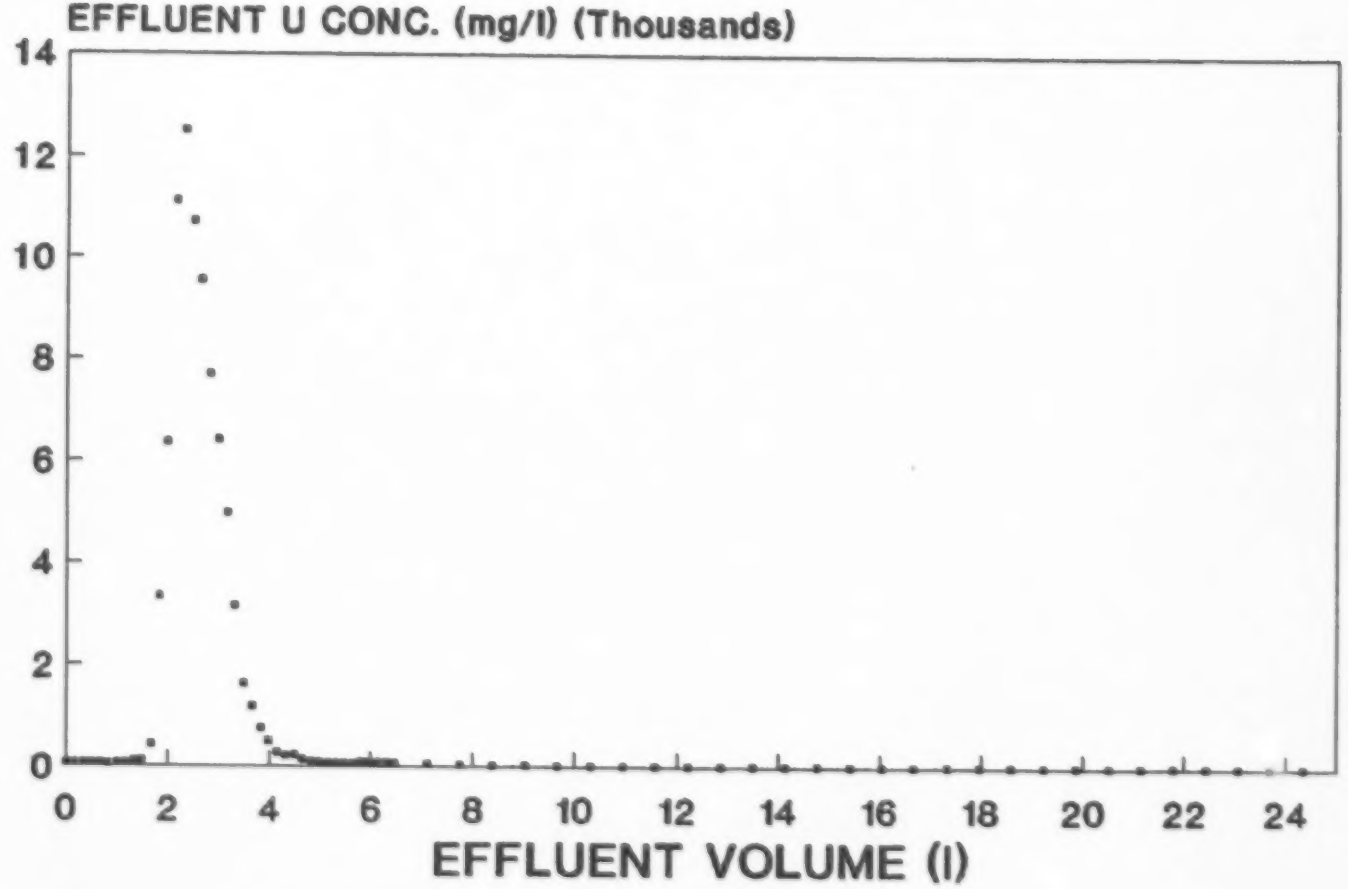

ELUTION BREAKTHROUGH CURVE
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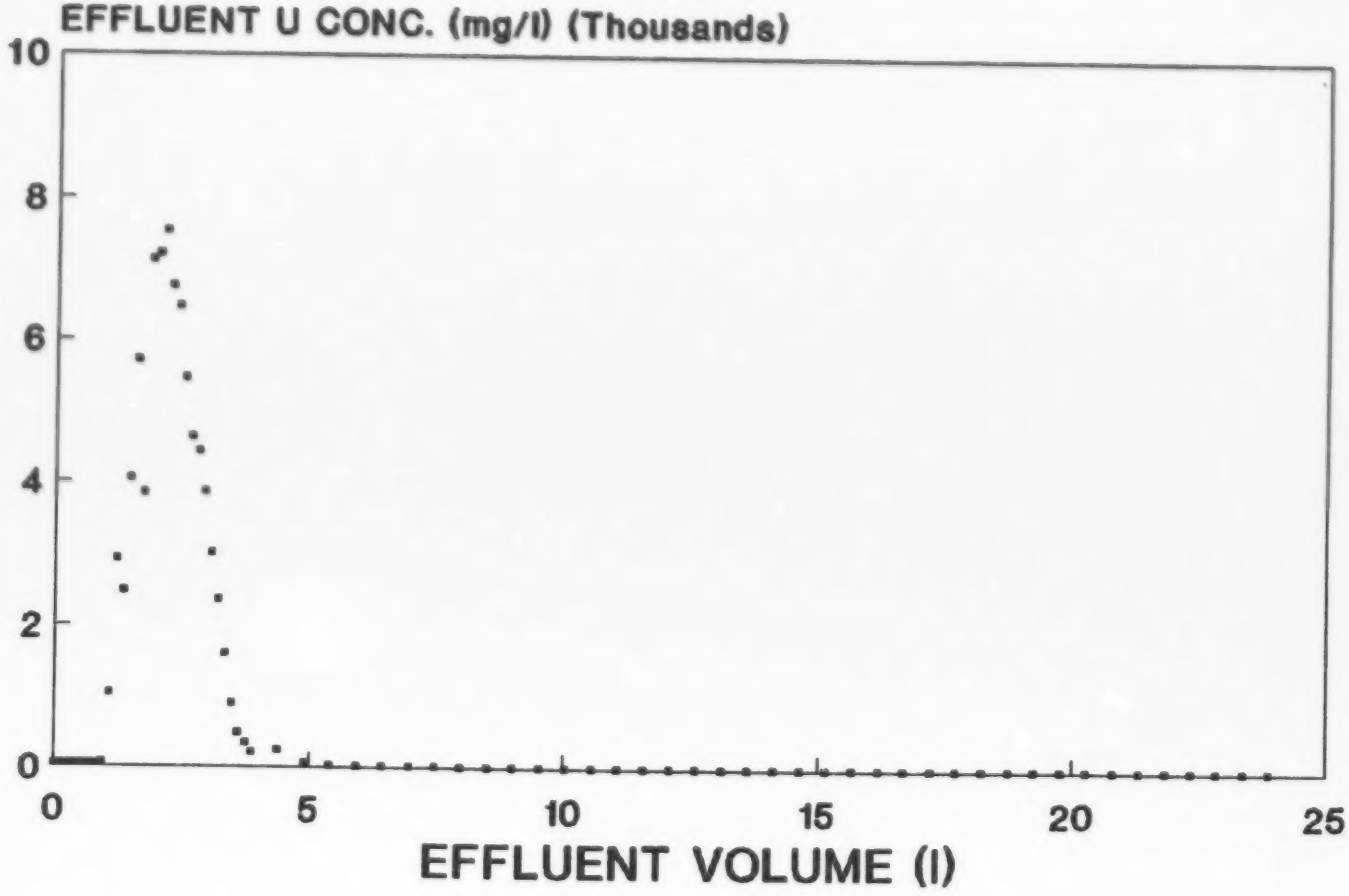

ELUTION BREAKTHROUGH CURVE
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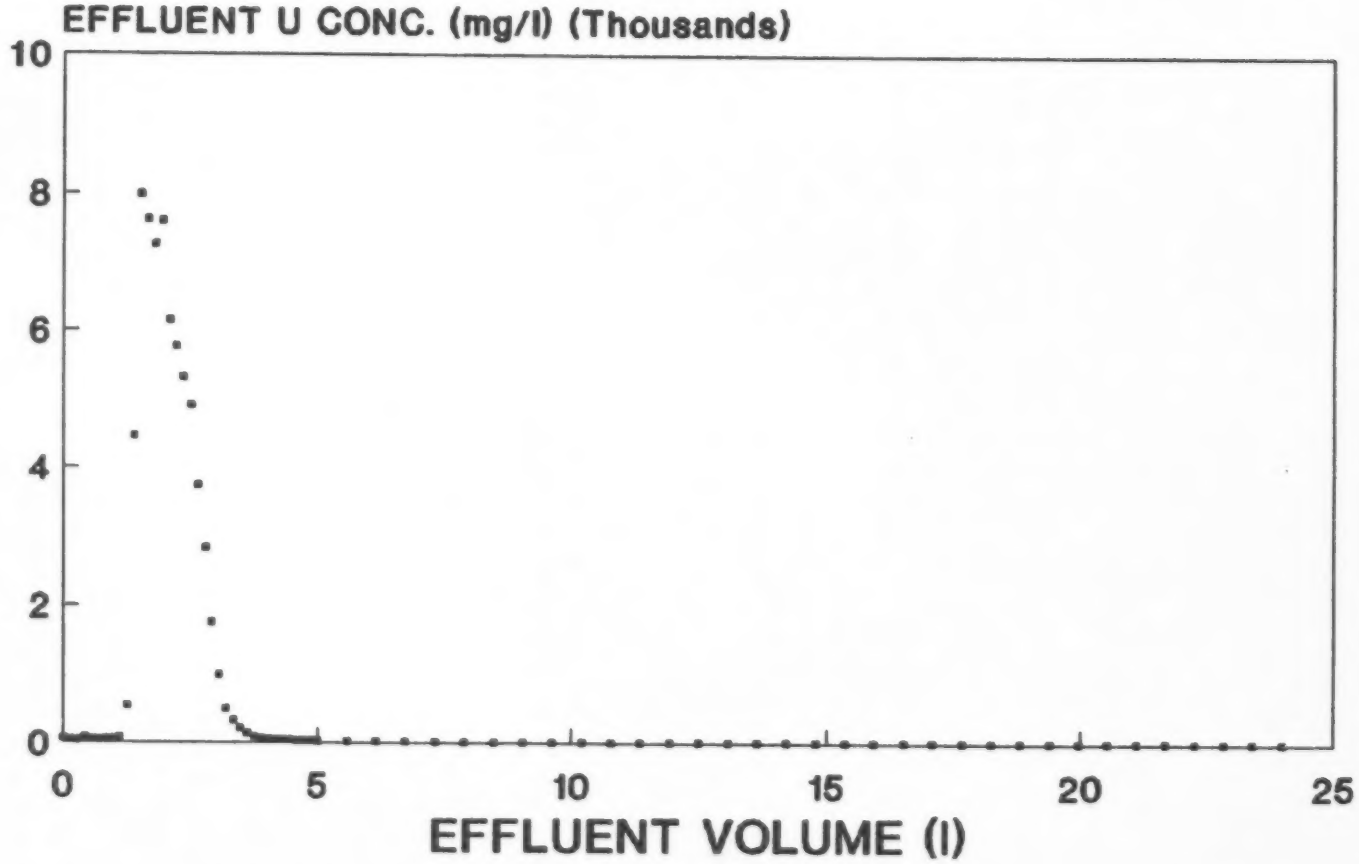

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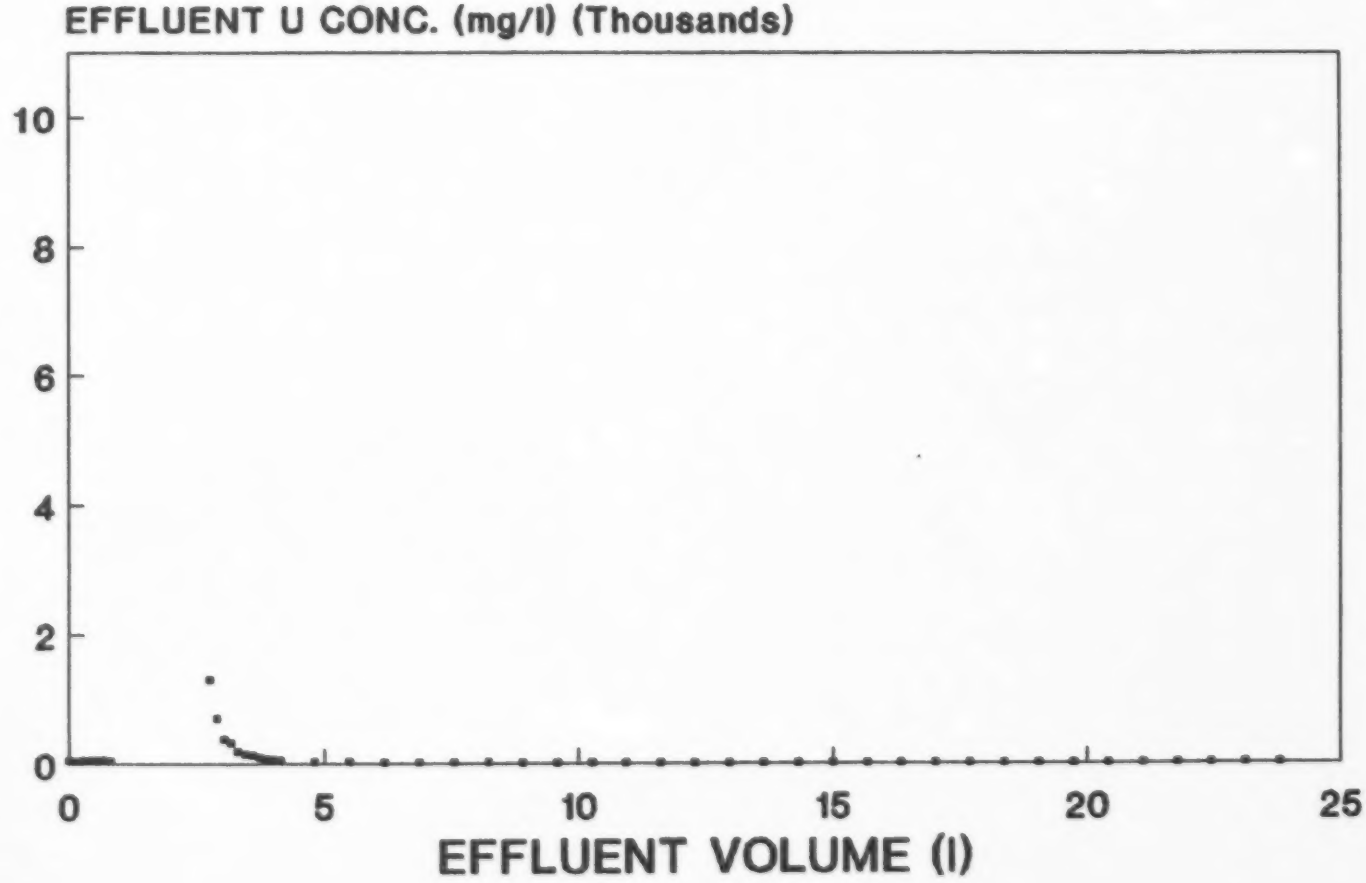

ELUTION BREAKTHROUGH CURVE
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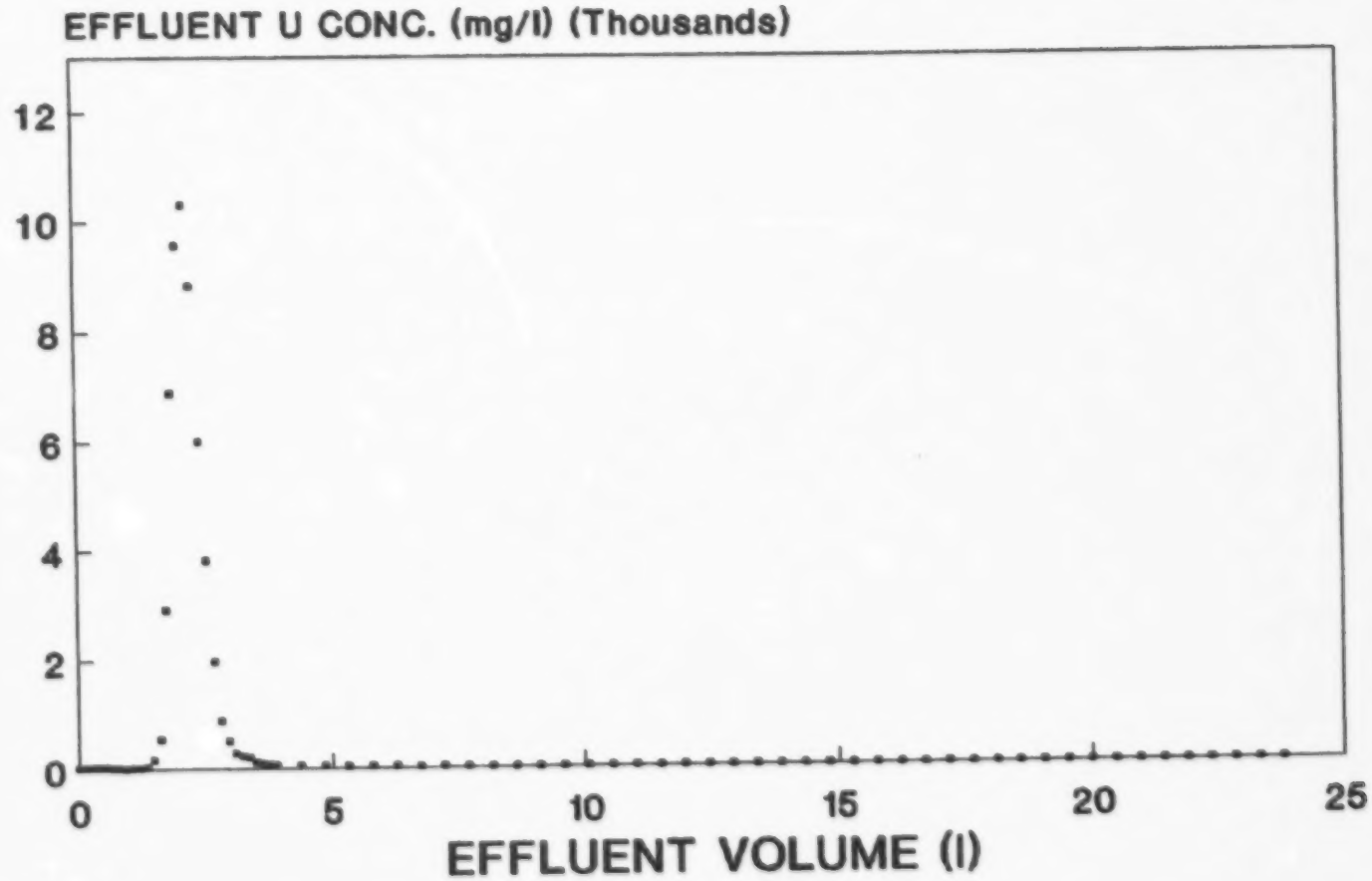
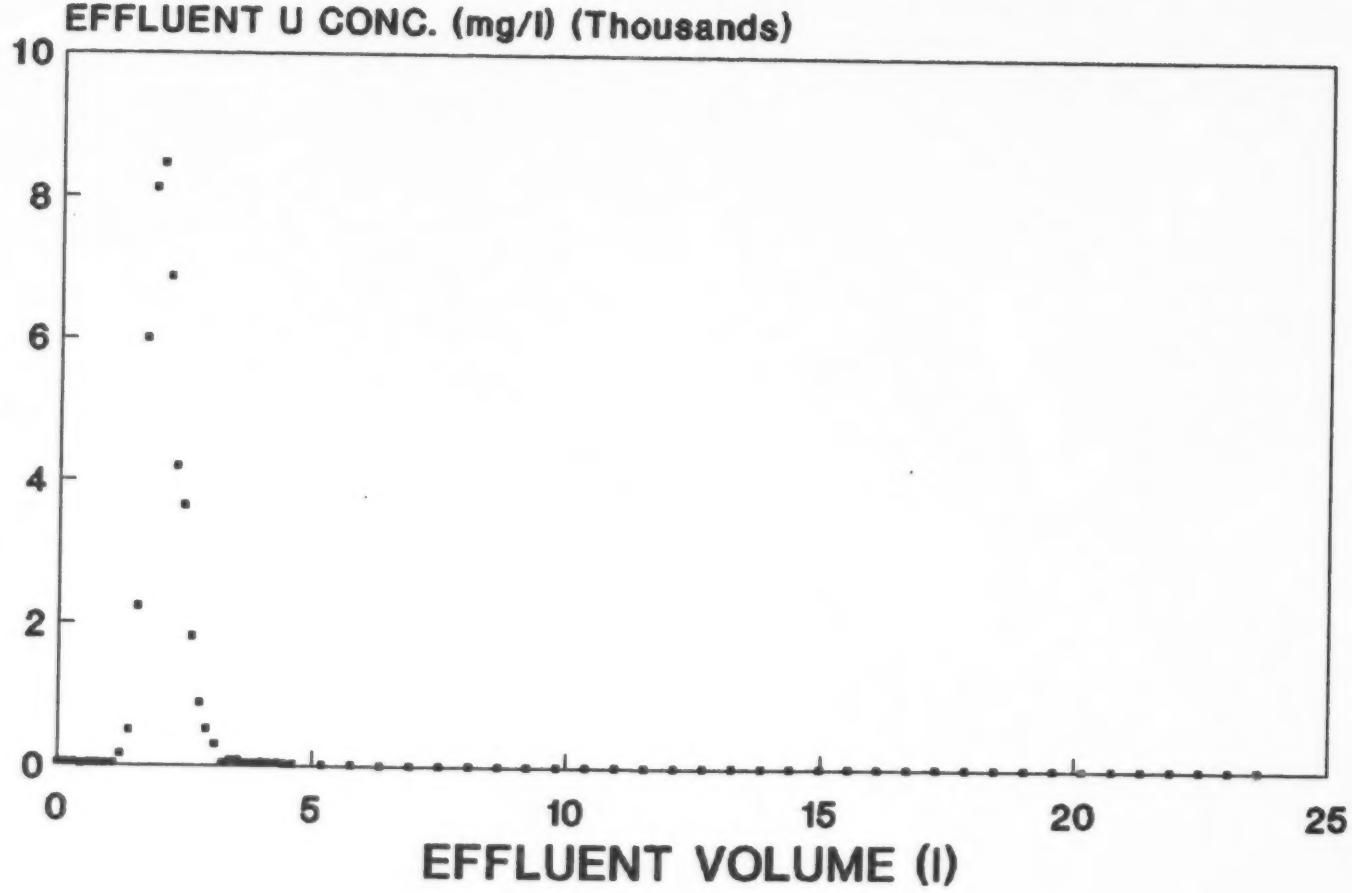
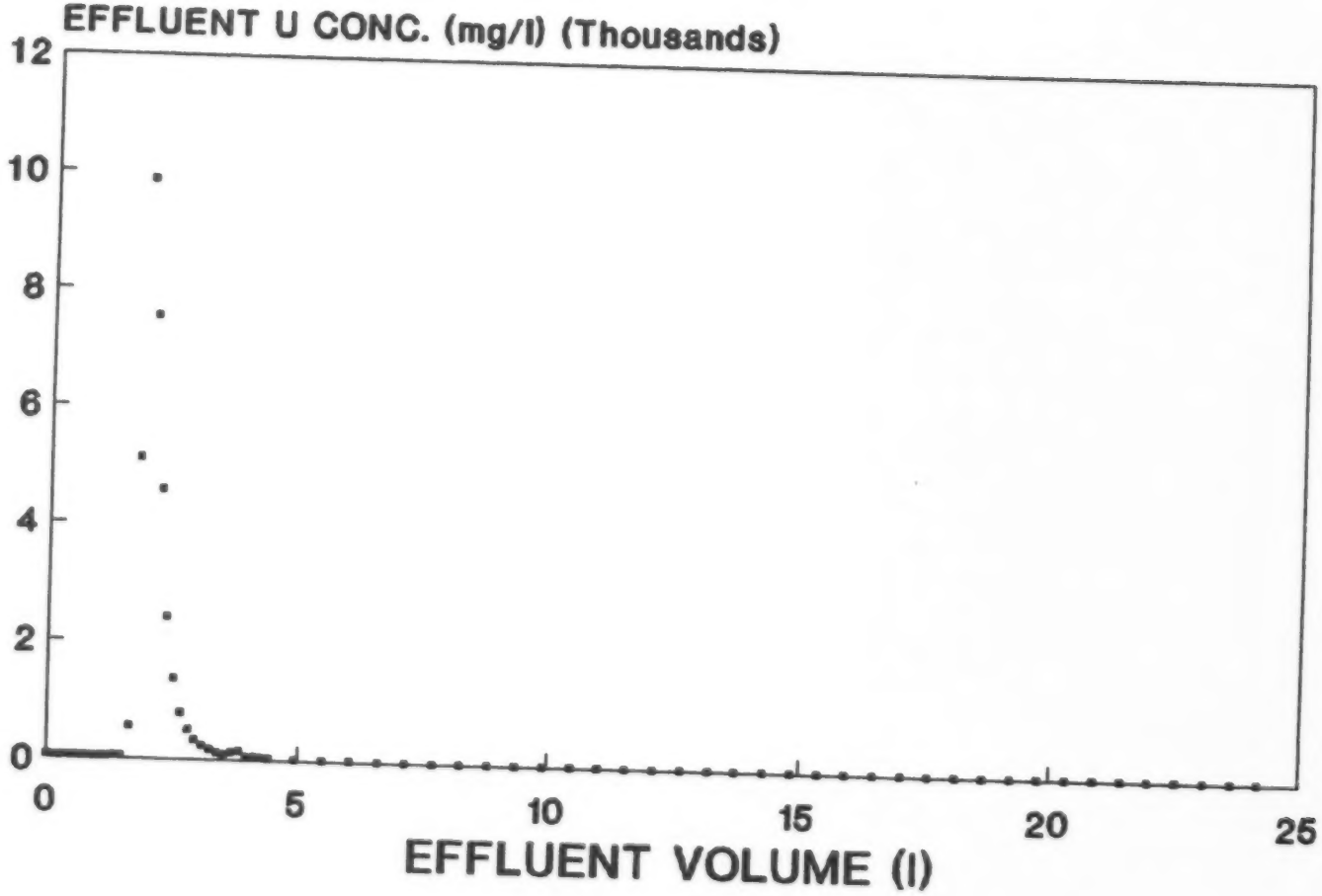


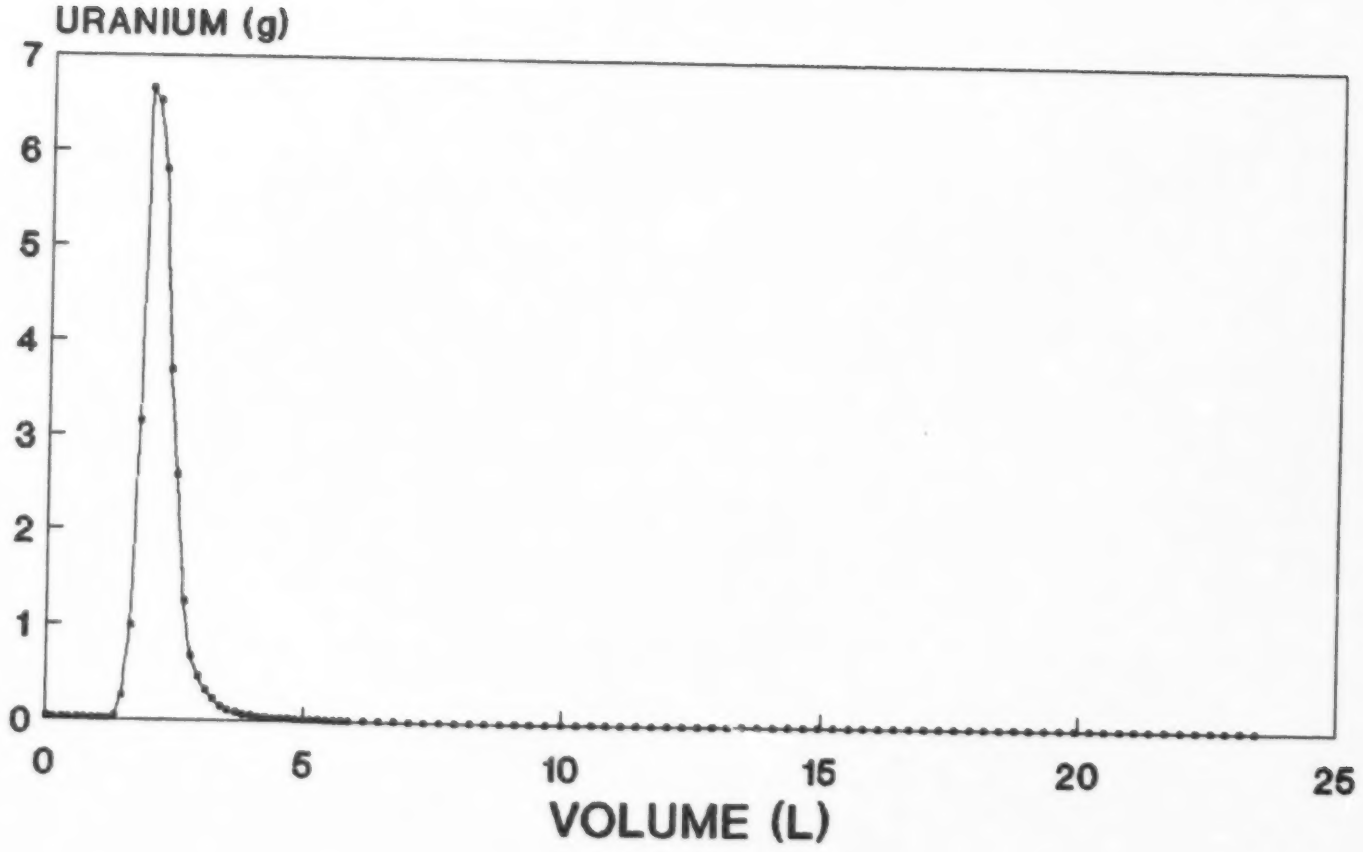
ELUTION BREAKTHROUGH CURVE
(Cycle 10)



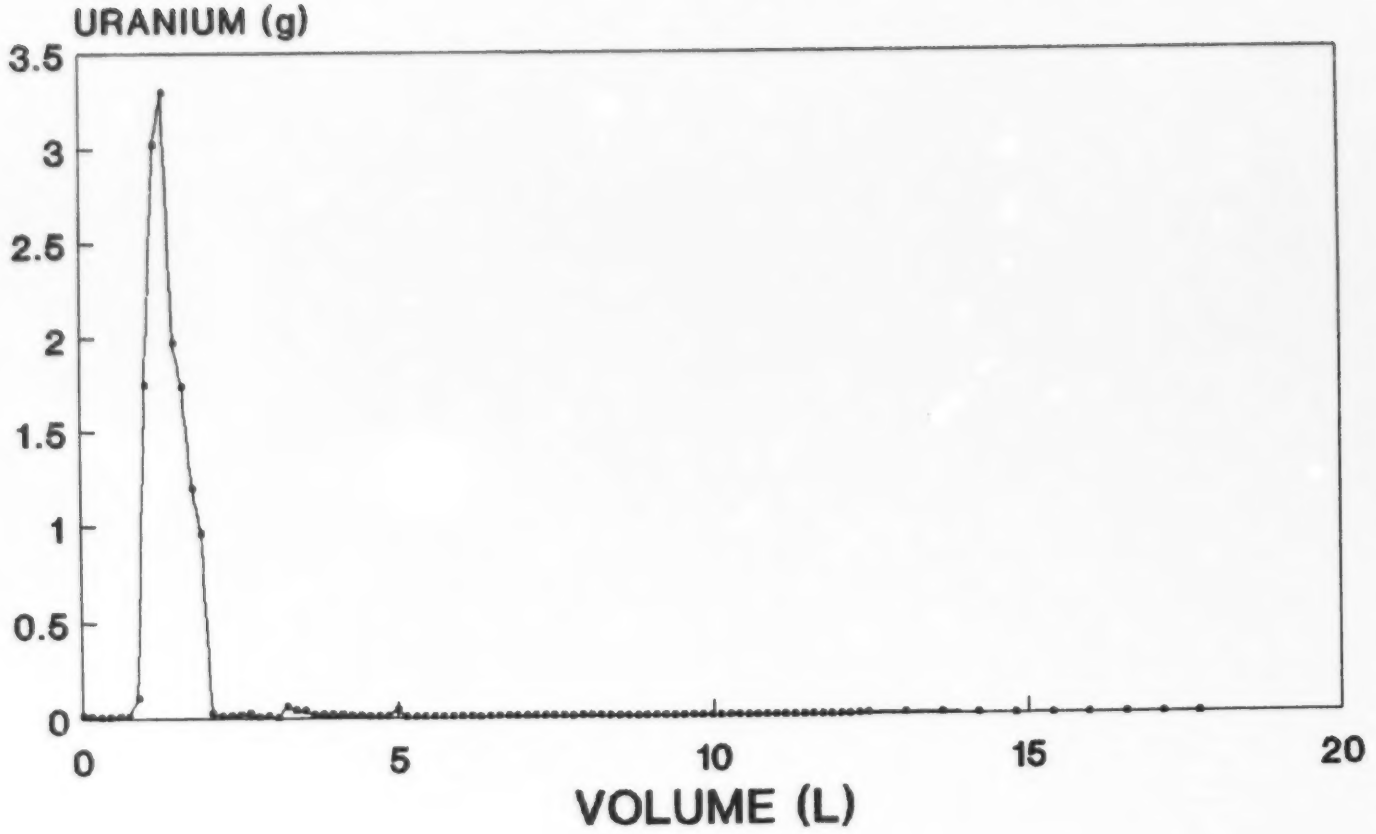
ELUTION BREAKTHROUGH CURVE
(Cycle 11)



ELUTION
CYCLE 12



ELUTION
CYCLE 13



ELUTION
CYCLE 14